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Energy and Water Nexus: Water management framework for the development of shale resources in Mexico

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Energy and Water Nexus: Water management framework for the development of shale resources in Mexico

by

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Dedicated to my wife Marifer and my daughter Almudena. I am and will always be grateful for your unconditional love and support.

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Energy and Water Nexus: Water management framework for the development of shale resources in Mexico

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Mexico is going through a historical moment due to eleven national structural reforms, including an energy reform approved in December 2013. This reform is expected to intensify production and other activities along the energy supply chain. Due to the relationship and dependency of energy and water systems, it is important to understand the impacts on water resources derived from the prospective increase on energy projects. In particular, an increase in water usage in water stressed areas could come from the expected development of shale resources through the combination of hydraulic fracturing and horizontal drilling (HF). The main goal of this research is to develop a framework to assist assessments of the current water available for HF in Mexico, and to analyze potential strategies that could increase the water availability to include HF users in Northern Mexico. The methodology conducted included (1) a spatial multilayer analysis that overlays the water availability in the watersheds and aquifers with the shale resources areas, (2) a decline curve analysis that estimates the potential produced water from HF users that could be reused to develop more shale resources, and (3) case studies that evaluate the potential increase in water availability for HF users due to a technology shift of current users (e.g. power plants

and irrigation districts), including an estimation of the water prices required to offset the costs implied on these shifts. Results suggest the following:

1. Between 8 and 70 Quadrillion British thermal units (Quads) of energy in the typical 20-30 year lifetime of the HF wells could be supplied with the average annual water available in aquifers and watersheds overlaying the 5 prospective shale basins in Mexico (e.g. Burgos, Sabinas, Tampico, Tuxpan, and Veracruz). However, geographic variation in water availability could represent a challenge for extracting the shale reserves. Most of the available water is located closer to the Gulf of Mexico, but the areas with the larger recoverable shale reserves (e.g. Burgos and Sabinas basins) coincide with less water availability in Northern Mexico.

2. The potential produced water from HF activity in three prospective areas analyzed in Northern Mexico, could be reused to extract around 0.02 to 0.06 and 0.04 to 0.1 Quads of energy in the overlaying oil and dry gas areas in the Burgos Basin throughout a 20-year period. This energy would represent from 0.4% to 1% and 0.01% to 0.03% of the recoverable resources in these areas.

3. Shifting the technology of two coal fired power plants (CPPs) to natural gas combined cycle (NGCC) in Northern Mexico would save enough water annually to supply HF wells that could extract between 0.7 and 1.2 Quads in a 20-year period, which would represent between 11% and 18% of the recoverable resources of the overlaying shale area. The water prices required to offset the technology shift of the CPPs would range between \$1.3 and \$6.3 USD/m^3, which is similar to the price that HF users have paid in the Texas' Eagle Ford Shale (on average 3.9 USD/m^3 [1]).

4. Shifting the irrigation technology in each of the two districts analyzed in Northern Mexico would save enough water annually to supply HF wells that could extract between 0.24 and 0.4 Quads in a 20-year period, which would represent from 0.1% to 0.15% and 4.2% to 7.5% of the overlaying shale areas of each irrigation district. The water prices required to offset the shift in irrigation technology in the districts would range between \$0.03 and \$0.09 USD/m^3, which is about 2 orders of magnitude smaller that the water prices required to offset the shift in technology of the CPPs.

The results of this research could inform decision makers and different players in the region (e.g. irrigation districts, and industrial users) of potential strategies and collaboration opportunities with the prospective HF projects in Northern Mexico. Future research could evaluate other water supply alternatives for potential HF users, such as (a) the use of degraded water quality sources, (b) the construction of potential projects to transfer water from different watersheds or aquifers, or (c) the use of non-aqueous fracturing fluids.

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Chapter 1

Introduction

1.1 Background and Motivation

1.1.1 Mexico's Energy Reform

In 2013, Mexico passed eleven national structural reforms that aim to modernize the country's economy. One of the most relevant is the energy reform approved in December 2013 [12, 13]. Before the energy reform, Mexico's government monopolized the oil and gas industry for approximately 70 years, and the electricity sector for around 55 years. This reform ends this monopoly with the intent of boosting Mexico's energy industry by fostering competitiveness and private investment throughout the energy value chain [14].

In the oil and gas industry, private investment is expected through service contracts, profit sharing agreements, and licenses [15]. Mexico's Oil Company (Pemex) will transform into a company of the state that will collaborate through profit and/or production sharing agreements [16]. In the electricity sector, a wholesale electricity market has been implemented in which the generation is open to private investment. The state will control the transmission and distribution of electricity assuring an open and nondiscriminatory access to all market participants [17], and Mexico's Federal Electricity Commission (CFE) will go through a vertical and horizontal unbundling process [18].

Energy and water are closely related to one another. Energy is used for the collection, treatment, conveyance, distribution, release, and other stages of the water sector [19]. On the other hand, water is used in power plants for cooling, hydroelectric power plants for electricity generation, in oil and gas operations, and other activities of the energy industry [20–23]. This relationship may cause constrains and challenges to potential projects triggered by the energy reform. Therefore, it is relevant to evaluate the potential implications of Mexico's energy reform in the water sector and of Mexico's current water availability in potential projects in the energy industry.

1.1.2 Shale Resources in Mexico

The combination of horizontal drilling and hydraulic fracturing (HF) in the United States enabled extraction from gas and tight oil shale reserves previously deemed uneconomic, and led to an increase in oil and gas production [24–26]. It is expected that these technologies could enable extraction of Mexico's shale resources, as well. Mexico is considered to be one of the top ten countries in terms of technically recoverable shale resources in the world [27,28] and its government, due to the energy reform, expects to triple its current gas production by developing HF wells in its shale basins [29,30].

Mexico's shale resources are located in five main basins, which have combined risked technically recoverable reserves (RR) of 545 Trillion cubic feet (Tcf) of gas and 13.1 Billion barrels (Bbbl) of oil [2,3], equivalent to approximately 636 Quadrillion British thermal units of energy (Quads) [31]. The 5 shale basins in Mexico, described in Table 1.1 and shown in Figure 1.1, are Burgos, Sabinas, Tampico, Tuxpan, and Veracruz. The Burgos Basin has 70% of the risked recoverable shale resources in Mexico with 393 Tcf (404 Quads) of natural gas and 6.34 Bbbl (36.722 Quads) of oil, which could cover Mexico's energy consumption for around 50 years at the rate of 7.5 Quads/year [2,32]. These resources are located in two main formations: 1) Mexico's Eagle Ford Shale (EFS), and 2) La Casita. Mexico's EFS is the extension of its Texas equivalent and is the top ranked shale prospect in Mexico.

Table 1.1: The largest recoverable reserves (RR) in Mexico are located in the Burgos Basin (around 70%). Furthermore, most of the RR are located in shale gas areas [2,3].

Basin	Area (mi^2)	RR Oil (Bbbl)	RR Gas (Tcf)	Energy for RR (Quads)	Percentage of Mexico's RR (%)
Burgos	24,200	6.3	393.1	441	69.34
Sabinas	35,700	0.0	123.8	127	19.96
Tampico	26,900	5.5	23.2	56	8.81
Tuxpan	2,810	1.0	1.5	7	1.11
Veracruz	9,030	0.3	3.4	5	0.78
Mexico	98,640	13.1	545	636	100

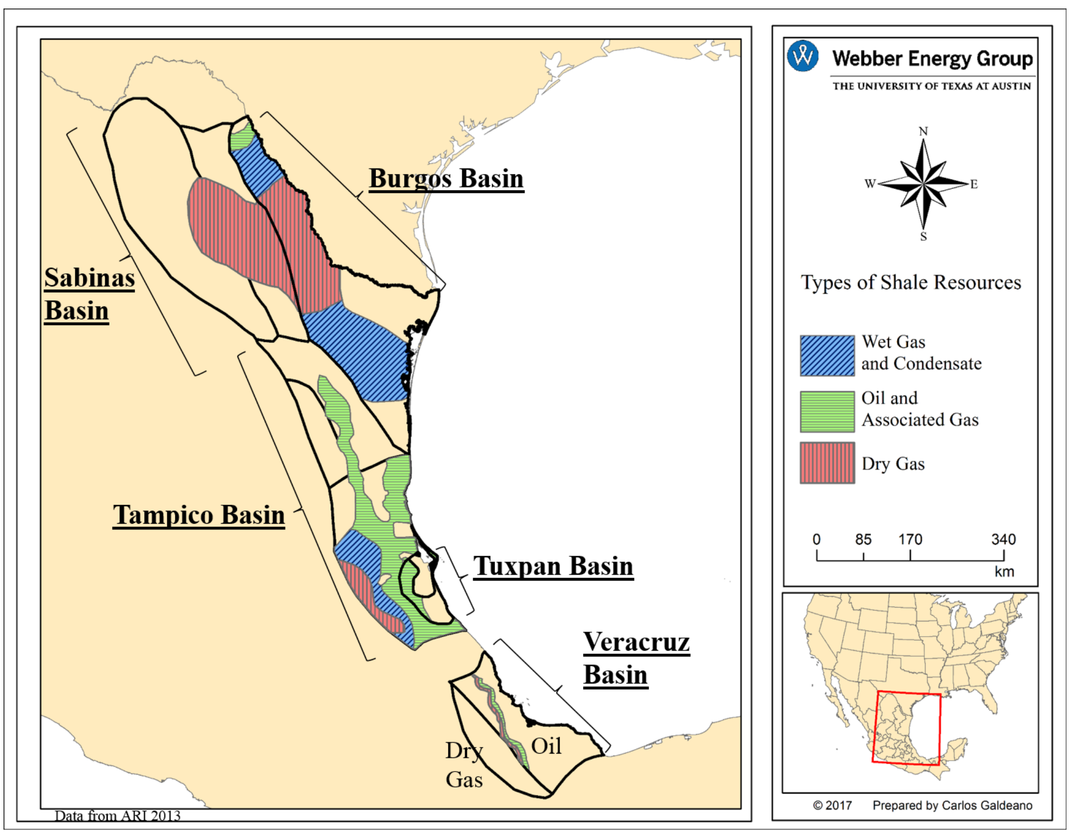

Figure 1.1: There are five continental shale basins in Mexico that have around 636 Quads of recoverable reserves (RR) combined [2,9].

In 2015, Mexico's Department of Energy (SENER) published a 5-year plan, which was updated in 2017, describing the prospective oil and gas areas intended to be explored and developed [33]. Among the prospective areas enlisted in the updated plan, 150 are onshore unconventional areas with RR of around 179 Quads (Figure 1.2) [10]. SENER has scheduled the first bidding round of shale resources blocks for September 2018, which include nine areas [34]. These nine areas cover a surface of 2,704 square kilometers in Tamaulipas and have a RR of around 6.4 Quads. These blocks were listed in a bidding round in 2015, but were rescheduled due to lack of environmental regulations for HF [35].

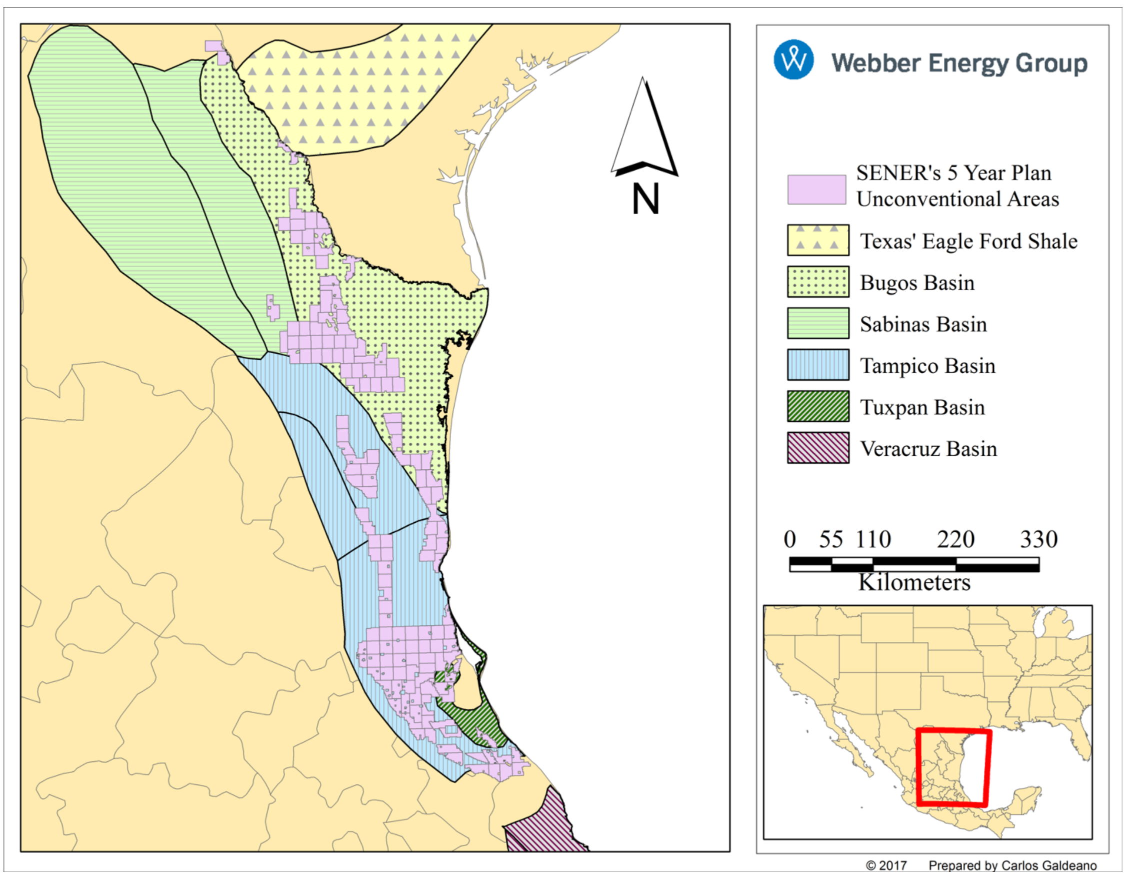

Figure 1.2: SENER's 5-year plan includes 150 unconventional areas with RR of around 179 Quads of energy [10].

1.1.3 Water Challenges of Hydraulic Fracturing

Even though the shale revolution started in the late 2000s, horizontal drilling and hydraulic fracturing have been employed since the 1930s and 1950s, respectively. The combination of these two methods, along with a mix of chemicals, have made the development of shale resources economically feasible [26]. Since the shale revolution started, a significant amount of research has been conducted to evaluate HF environmental and social challenges [36]. The main challenges include the water quantity it requires, the large volume of wastewater it produces, the induced seismicity from the deep well injection of the produced water, the on-site natural gas flaring, the air emissions from trucking and the on-site equipment required, and the traffic increase in local roads [4, 37–44].

In particular, the impacts on the water required for HF vary depending on the water availability and competing demands at a local level [45, 46], but it is important to understand the sources and intensity of water used for HF to evaluate its full impacts on the water resources [47]. Water intensity for HF varies on several factors such as depth, type of shale resources, and thickness of each formation [7]. The water required per HF well has been increasing throughout time due to changes in technology and practices [6, 48], although the productivity of energy extracted per well has also been increasing [6, 7]. In 2013, the average water consumption per well in the EFS in Texas was about 4.9 million gallons per well (Mgal/well) [49], whereas in 2016 it was around 8.77 Mgal/well [50]. On the other hand, when analyzed on a per unit of energy basis, HF has required between 1×10^9 and 28×10^9 gallons of water per Quads (gal/Quads) in gas areas, and between 1.5×10^9 and 21.7×10^9 gal/Quads in tight oil areas [4]. In the EFS formation in Texas the average water required in the oil and gas shale areas, based on the wells estimated ultimate recovery, is 2.6×10^9

and 1.5×10^9 gal/Quads [49]. The estimated ultimate recovery (EUR) is defined as the approximate quantity of shale resource that could be recovered throughout a typical 20-30 year lifetime of a hydraulic fracturing well [49].

Even though HF is considered a water-intensive activity, when compared with other high-water users, such as irrigation, it has been relatively small [1, 51]. Nevertheless, HF has been the major water-intensive user in some counties in Texas [52]. Due to the high water demand that HF could cause at a local level, different strategies to increase water availability and decrease water stress in the regions where shale resources are located are worth analyzing. These strategies could include (1) shifting to less water intensive power plant technologies, (2) shifting to more efficient irrigation technologies, (3) using brackish groundwater as a source of water for HF, and/or (4) recycling and reusing wastewater (e.g. flowback and produced water) that will return to the surface over the lifetime of the HF wells, which in Texas shale areas ranges from 15% to 200% relative to the water demand of the HF wells [36, 53].

Some research has been conducted to analyze and evaluate the increase in water available from these potential strategies. For instance, despite the potential increase of water consumption from HF in Texas, it has been shown that in switching from coal-fired to natural gas combined cycle, power plants could reduce water consumption by approximately 60% because of more efficient energy conversion and less water-intensive cooling systems at the power plant [54]. Also, it has been shown that it is possible to increase water availability in the shale regions by using the energy wasted in flared gas activities from HF to treat and reuse the flowback and produced water (PW) [37]. In 2012, the flared gas in Texas could have been used to treat between 180 and 540 million cubic meters (Mm^3) of these wastewater, which is around 1% to 2.4% of Texas' annual water demand [36].

1.1.4 Mexico's Watersheds and Aquifers Classification

Mexico's water availability varies across the country. Mexico's Water Commission (Conagua) classifies the water availability of the aquifers and watersheds based on four zones that depend on a groundwater availability index (GWAI) and a surface water availability index (SWAI), respectively [55]. These indices are used as thresholds to assign a water price to users [56, 57]. For both indices, the areas classified as Zone 1 represent the areas with greater water scarcity and higher water prices. On the other hand, the areas classified as Zone 4 have plenty of water available and the water prices range, depending on the use (e.g. municipal, industrial, agricultural), from 10% to 15% of those in Zone 1 areas [56].

Figure 1.3 shows the classification of Mexico's aquifers and watersheds based on the indices established by Conagua. According to the corresponding index, about 38% of the watersheds in Mexico are classified as Zone 1 (greater water scarcity) and about 23% of the aquifers are classified as Zone 1. Most of the watersheds in Central and Northern Mexico lack of water availability, which could impose challenges to potential projects triggered by the energy reform.

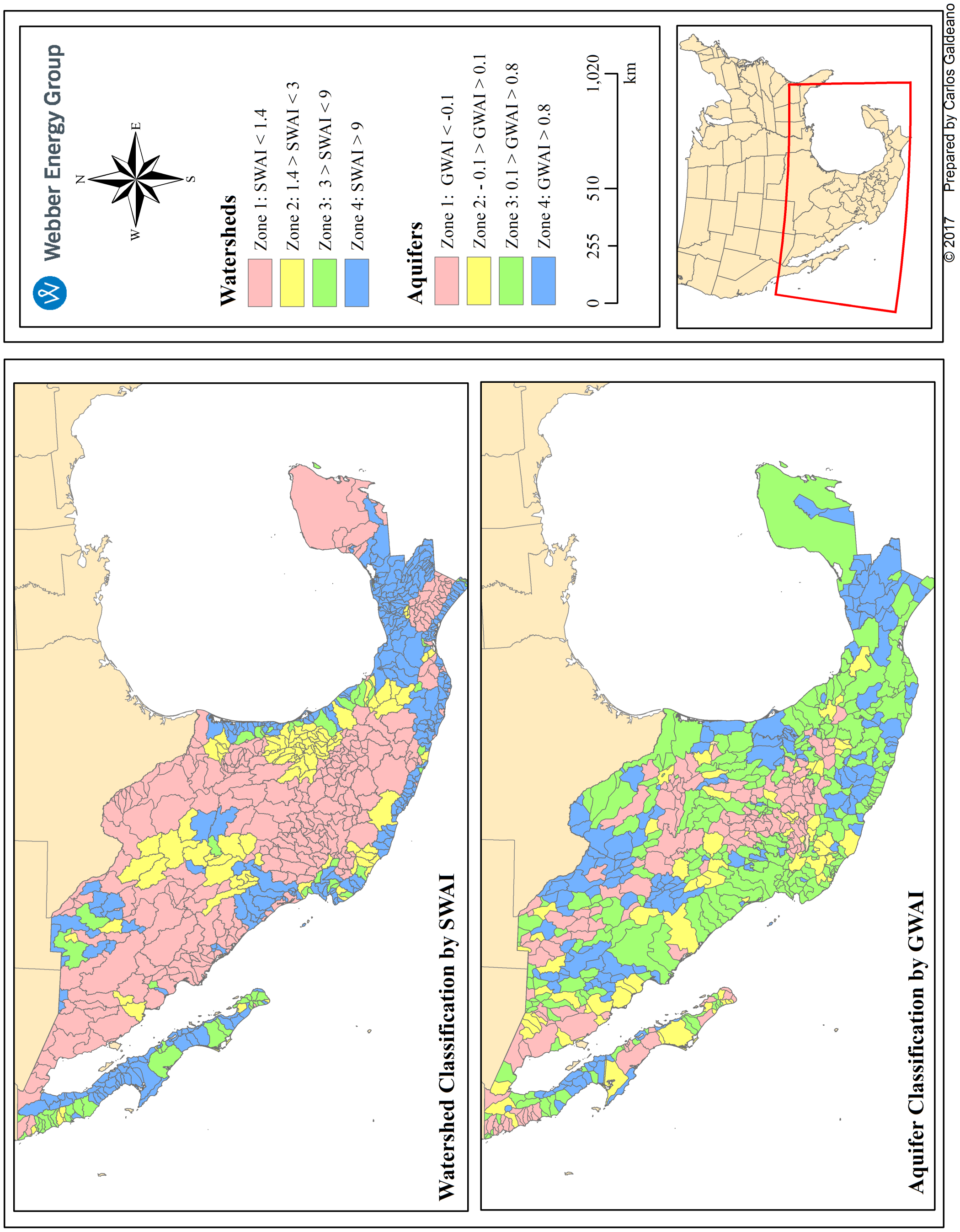

Figure 1.3: Conagua classifies the water availability of Mexico's watersheds and aquifers in four zones that depend on a GWAI and SWAI [11].

The surface water basin that overlays the shale area with larger RR (Burgos Basin) in Mexico is the Rio Grande/Bravo (RGB) basin (Figure 1.4), which have over allocated water rights [58–61] and is considered to be in a medium to high water risk [62]. The principal surface water demands in the RGB basin are municipal and agricultural at 11% and 88%, respectively [60]. Due to the complexity of this transboundary basin, two treaties were signed between the U.S. and Mexico (1906 [63] and 1944 [64]) to determine the water management strategies and allocation along the river. Furthermore, the International Water Boundary Commission (IWBC) was created in 1944 to foresee the compliment of the treaties and to enhance a better communication between both sides of the border [65].

The decision of the IWBC after a dispute is recorded as a "Minute", which becomes binding within 30 days unless it is disapproved by the U.S. or Mexican authorities. Among these Minutes, the resolution of disputes regarding the Mexico's water debt from the 1999—2002 period is included (Minute 308 [66]). Additionally, a Minute that describes the investment on more water efficient irrigation technologies and practices from three Mexican irrigation districts in 2004 is included too (Minute 309 [8].

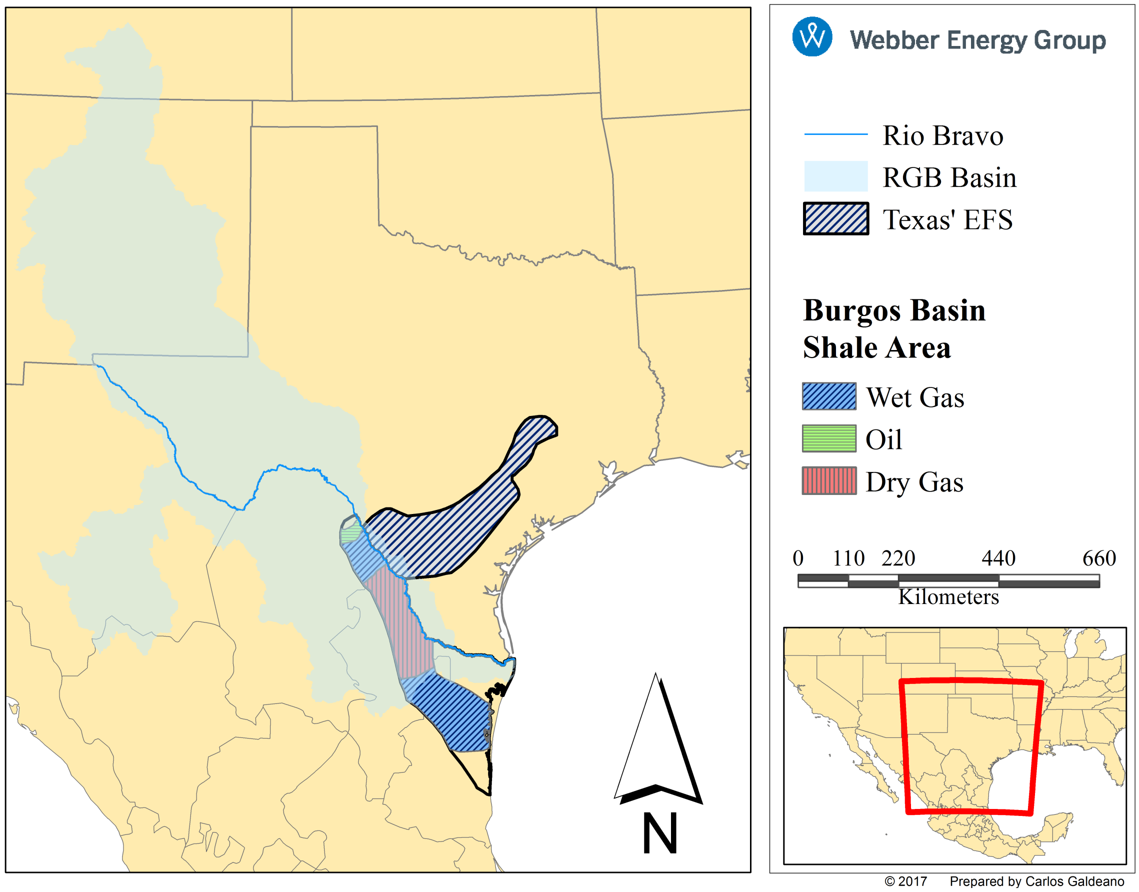

Figure 1.4: The Rio Grande/Bravo, which has overallocated water rights and is under water stress, overlays the Burgos Basin, which has 70% of Mexico's RR of shale resources.

1.2 Scope and Organization

Even though significant research has been conducted to understand the water challenges and impacts of HF, little research has focused on developing methodologies that assist in evaluating current water available and potential strategies to increase water availability in prospective shale resources areas. The overall scope of this research is to develop a framework to analyze water availability and water management strategies to include potential new HF users in water stressed areas. This framework

(Figure 1.5) centers on (1) estimating the water available in aquifers and watersheds overlaying the shale resources, and (2) analyzing different strategies to increase water availability for HF. These strategies are grouped in the following two mutually exclusive and collectively exhaustive areas:

1. Using water that is not located in the system (e.g. brackish groundwater, transfer water from different watersheds or aquifers, and reuse of PW from HF activities).

2. Using water that is in the system and has already been committed to other users (e.g. irrigation districts, and industrial users).

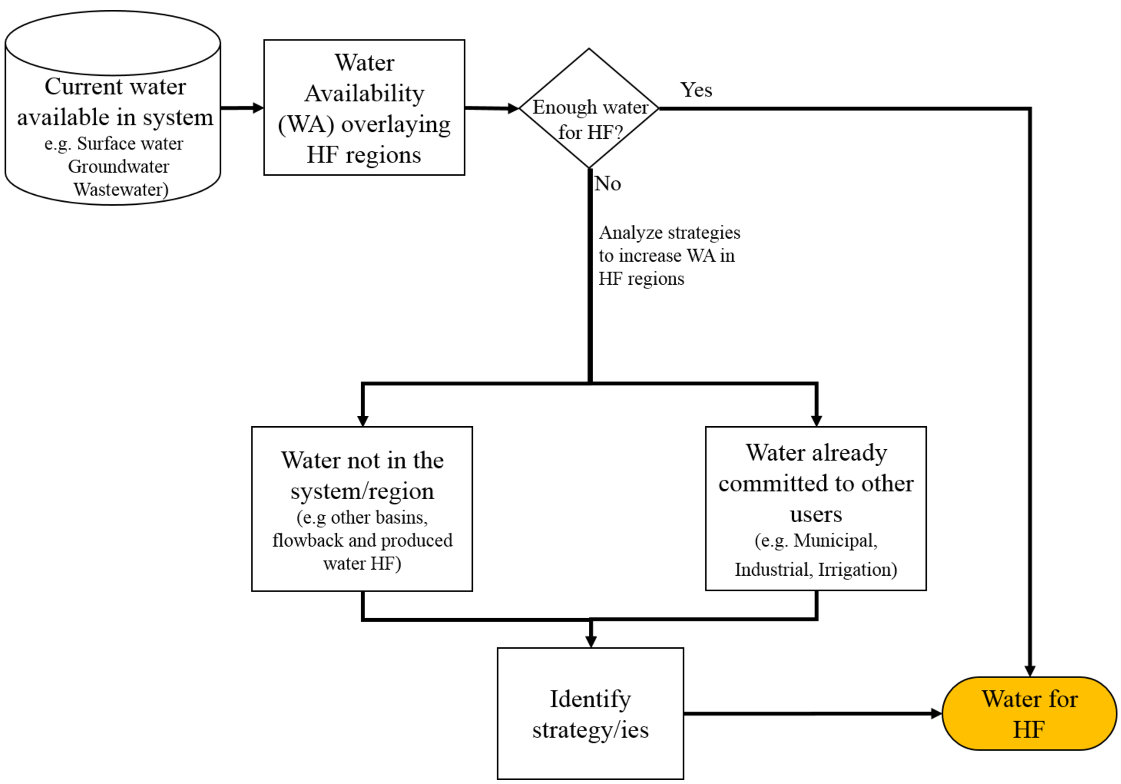

Figure 1.5: The framework proposed centers in (1) estimating the water available in aquifers and watersheds overlaying the shale resources, and (2) analyzing different strategies to increase water availability for HF.

Following this framework, this dissertation has three major goals that include:

1. Determining current water availability in the aquifers and watersheds overlaying the prospective shale resources in Mexico.

2. Estimating the potential PW from HF that could be reused to develop shale resources in prospective areas in the Burgos Basin across the border with Texas.

3. Evaluating the potential increase in water availability for either current users (e.g. irrigation districts) or potential HF users in the middle and lower Rio Grande/Bravo basin (RGB) due to a shift of:

   (a) current energy production facilities to more efficient energy sources (from coal to gas) and power plant technology (from steam cycle to combined cycle), including an estimation of the breakeven prices at which the surplus water sales plus the economic benefits from shifting the technology and energy sources would offset the costs implied on this shift.

   (b) current irrigation practices and technologies to more water efficient technologies and practices, including an estimation of the breakeven price at which the surplus water sales would offset the investment cost of the irrigation improvements.

These goals are addressed through research and analysis presented in the following chapters. Chapter 2 describes a multilayer geospatial analysis conducted to estimate the average annual water availability for shale resources development in Mexico. The main contribution in Chapter 2 is the development of a methodology that identifies the spatial location and volume of water available in the aquifers and watersheds overlaying the shale areas. This methodology could assist as a starting point in the development of strategies for managing the water resources available to integrate HF users in Mexico without depleting the water in aquifers and watersheds.

Chapter 3 describes a temporal analysis conducted to asses potential reuse of produced water from hydraulic fracturing. The main contribution in this chapter is the development of a methodology that forecasts the potential produced water from HF that could be reused to develop shale resources in water stressed areas. This methodology was employed in three prospective unconventional areas to be developed in Northern Mexico. Furthermore, the methodology developed could assist policymakers in analyzing and implementing further regulations to include PW reuse as a water management strategy in the development of shale resources in Mexico.

The following two chapters (Chapter 4 and 5) describe case studies in which a water allocation model of the RGB is modified to analyze potential scenarios of water management strategies triggered by Mexico's energy reform. The main contribution in Chapter 4 is the development of a methodology that assesses the potential changes in water availability in a water stressed area due to a shift of current energy production facilities to more water efficient energy sources (from coal to gas) and power plant technology (from steam cycle to combined cycle). On the other hand, the main contribution in Chapter 5 is the development of a methodology to assesses the potential changes in water availability in a water stressed basin due to a shift of current irrigation technologies to more water efficient practices. Finally, Chapter 6 summarizes the conclusions of this research and suggests future work to be considered.

Chapter 2

Assessing water availability for shale resources development in Mexico

2.1 Introduction

The classification of the watershed and aquifers overlaying the prospective shale resources in Mexico, according to the Surface Water Availabilty Index (SWAI) and Groundwater Availability Index (GWAI) estimated by Conagua, is shown in Figure 2.1. In Northern Mexico, most watersheds are classified as Zone 1, while closer to the Gulf of Mexico watersheds are classified as Zone 4. On the other hand, most of the aquifers overlaying the shale areas are classified in a better category (Zones 3 and 4). The aquifers with saline or brackish groundwater are reported every year by Conagua, but the breakdown of the volumes are not reported [67–69]. Of the aquifers overlaying the shale basins, the Bajo Rio Bravo (No. 1 in Figure 2.1), Cuatrocienegas-Ocampo (No. 2 in Figure 2.1), Paredon (No. 3 in Figure 2.1), and El Hundido (No. 4 in Figure 2.1) have brackish groundwater [67–69]. The main contribution of this chapter is to develop a methodology to identify the spatial location and volume of water available in the aquifers and watersheds that overlay the five shale basins in Mexico. Furthermore, this chapter describes data, methods, and results used to

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identify the potential EUR energy that could be extracted over the 20-30 year lifetime of HF wells supplied with available surface and groundwater. The research presented in this chapter intends to assist as a starting point analysis for the development of strategies for managing the water resources available to integrate HF users in Mexico without depleting the water in aquifers and watersheds.

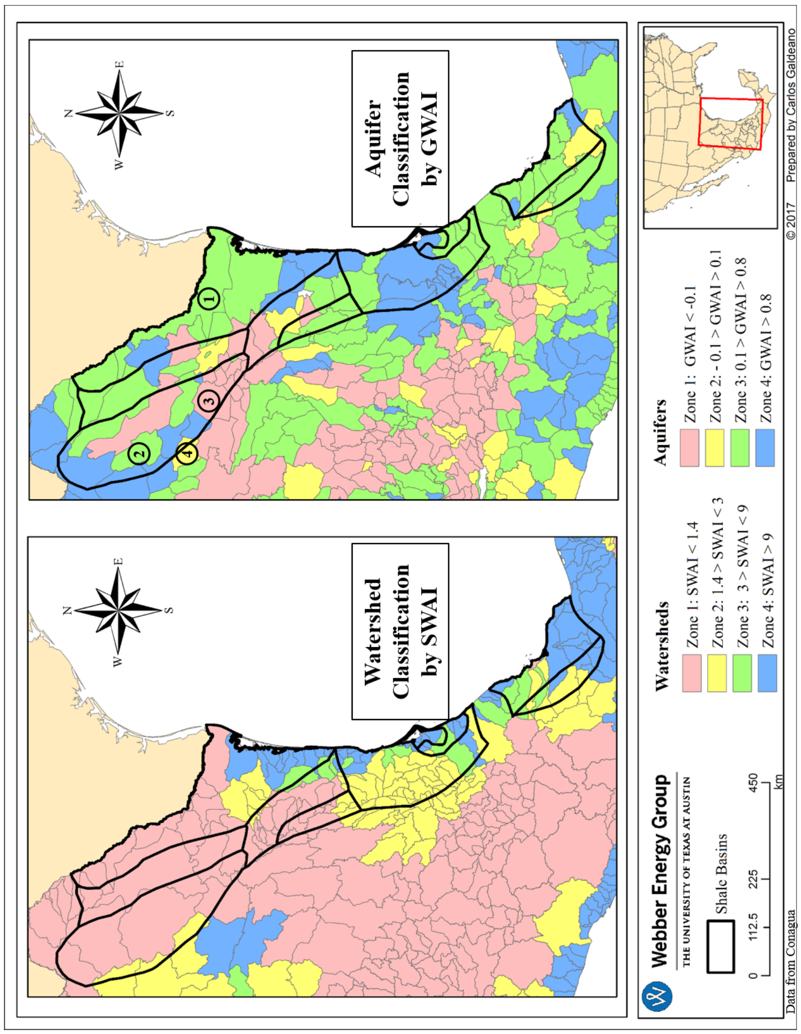

Figure 2.1: The watersheds and aquifers with worst availability overlap with rich oil and gas areas, raising the specter that water scarcity could hinder oil and gas production [11].

2.2 Methodology

The average annual water availability (WA) for HF in Mexico is estimated by using a multilayer geospatial analysis. This WA considers the average annual surface water and groundwater available to estimate the potential EUR shale reserves that could be extracted from the HF wells that could be supplied with this WA. The surface and groundwater data was provided by Conagua's Water Geographic Information System [70]. These data are based on average values from at least 20 consecutive years of historical records, or from values estimated by Conagua based on other hydrologic parameters (e.g. precipitation, type of soil, evapotranspiration) [71]. The average values are useful as a first approach to determine the WA in the areas analyzed, but future work should incorporate the raw historical data to understand the WA variation during dry and wet periods. Furthermore, the RR in each basin was taken into account in the analysis. The RR in each shale basin was obtained from the report prepared by the Advanced Resources International for the U.S. Energy Information Administration [2]. The potential WA for HF was estimated by intersecting the surface and groundwater availability in each shale area. The methodology is shown in Figure 2.2 and described below.

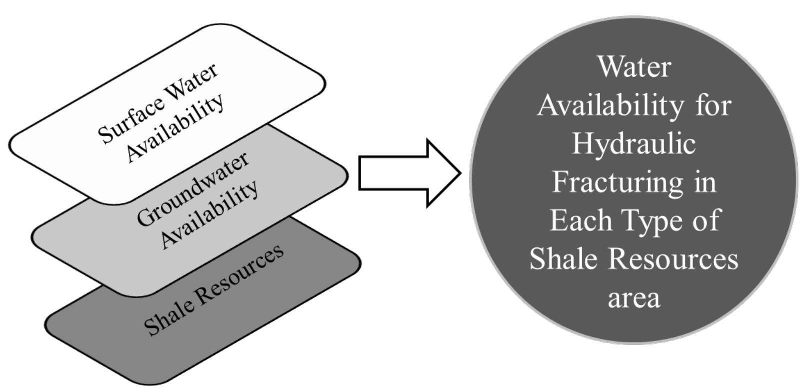

Figure 2.2: A multilayer geospatial analysis was conducted to determine the water availability in each type of shale resources area in Mexico.

2.2.1 Surface Water Availability

Following Conagua's methodology [71], the mean annual water available in the watersheds ($MASWA_i$) that overlay the shale areas is estimated using Equation 2.1:

$$MASWA_i = Inputs_i - Outputs_i \tag{2.1}$$

where $Inputs_i$ and $Outputs_i$ are the inputs and outputs of water to the watershed i, as shown in Table 2.1.

Table 2.1: Four water inputs and five water outputs were considered in each watershed to estimate its water availability.

Input or Output	**Variable**	**Definition [71]**
Input	Mean annual volume of natural runoff	Natural runoff of the watershed, estimated with either at least 20 years of historical data or the rational method.
Input	Mean annual volume of runoff from upstream watershed	Water that enters the watershed from the natural drainage of the immediate upstream watersheds.
Input	Annual volume of water imports	Water received by the watershed that does not drain naturally from other watersheds or aquifers.
Input	Annual volume of water returns	User return flow to the watershed, estimated by either direct measurement or an assumption that depends on type of user.
Output	Annual volume of surface water extraction	Water allocated for environmental flows and users registered in the Public Register of Water Rights.
Output	Annual volume of water exports	Water allocated to other watersheds in which there is no natural drainage.
Output	Annual volume of evaporation in reservoirs	Water evaporated from the reservoirs, estimated based on evaporation measurements applied to the free surface of the reservoir.
Output	Annual volume committed to downstream watershed	Water volume needed to drain to the immediate downstream watershed to meet its water users rights and environmental flows.
Output	Annual volume of variation on storage in reservoirs	Changes in water volume in the reservoirs due to changes in runoff regime, and policies in reservoir operations.

The $MASWA_i$ is assumed to be evenly distributed along each watershed i. A ratio is estimated to determine the mean annual surface water available (SWA_i) in the intersection of the watersheds and the shale areas using Equation 2.2:

$$SWA_i = \frac{SA_k B_j \cap A_i}{A_i} MASWA_i \tag{2.2}$$

where A_i is the area of the watershed i, and $SA_k B_j \cap A_i$ is the area of the intersection of the watershed i and the shale area k in the shale basin j.

Three different alternatives based on the four zones of WA that Conagua uses to classify Mexico's watersheds are analyzed using the SWA_i [55,68,72]. The $SWAI_i$ for each watershed is estimated using Equation 2.3:

$$SWAI_i = \frac{Inputs_i}{Outputs_i} \tag{2.3}$$

The ranges of the $SWAI$ used to classify Mexico's watersheds by zones are shown in Table 2.2. These zones are based on the WA in each watershed on ascending order from Zone 1 to Zone 4, and are used to determine the water prices. As shown in Table 2.2, the price per cubic meter of water in the watersheds classified as Zone 1, Zone 2, and Zone 3 are 766%, 299%, and 31% more expensive that in Zone 4.

Table 2.2: Zones of surface water availability and ranges of $SWAI$, where the best zone is 4 and the worst is 1. Low numbers of the $SWAI$ indicate more water scarcity, which translates into more expensive water for current and new users.

Zone	Range of SWAI	Increase in water price with respect to Zone 4
Zone 1	SWAI $<$ 1.4	766%
Zone 2	1.4 $>$ SWAI $<$ 3	299%
Zone 3	3 $>$ SWAI $<$ 9	31%
Zone 4	SWAI $>$ 9	-

The three different alternatives analyzed were:

- **Alternative 1.** This alternative evaluates the case in which all the SWA_i is supplied for HF in the intersection of the watersheds and the shale areas. Under this alternative, new water users could not be added, nor could current users increase their demand. Also, the water price for all users would be more expensive. This alternative provides an upper bound.

- **Alternative 2.** This alternative evaluates the case in which part of the SWA_i is supplied for HF, but leaving a $SWAI > 3$ (Zone 3). Under this alternative, new users could still be added or current users could increase their water demand, and the water price for all users would either remain the same or increase by around 31%.

- **Alternative 3.** This alternative evaluates the case in which part of the SWA_i is supplied for HF, but leaving a $SWAI > 9$ (Zone 4). Under this alternative, new users could still be added or current users could increase their water demand, and the water price for all users would remain in the cheapest price.

Equation 2.4 was used to determine the volume supplied for HF in alternatives 2 and 3:

$$x_i = \frac{Inputs_i}{SWAI} Outputs_i \tag{2.4}$$

where x_i is the water available to be supplied in watershed i by leaving a $SWAI$ greater or equal to 3 or 9 for alternatives 2 and 3, respectively.

2.2.2 Groundwater Availability

Following Conagua's methodology [71], the mean annual groundwater available from the aquifers ($MAGWA$) that overlay the shale areas were estimated using Equation 2.5:

$$MAGWA_i = R_i - NCD_i - GWE_i \tag{2.5}$$

where R_i is mean annual recharge in aquifer i, NCD_i is the natural committed discharge of aquifer i, and GWE_i is the extraction of groundwater for other uses. The NCD_i is defined as the volume of water from the aquifer committed to springs and rivers, while the GWE_i is determined by the volume of groundwater assigned to other users by Conagua [71].

The $MAGWA_i$ was assumed to be evenly distributed throughout each aquifer i. A ratio was estimated to determine the mean annual groundwater available (GWA_i) in the intersection of the aquifers and the shale areas using Equation 2.6:

$$GWA_i = \frac{SA_k B_j \cap AG_i}{AG_i} MASWA_i \tag{2.6}$$

where AG_i is the area of the aquifer i, and $SA_k B_j \cap AG_i$ is the area of the intersection of the aquifer i and the different shale area k in the shale basin j.

In similar fashion as for surface water, three different alternatives were analyzed using the GWA_i. These alternatives are based on the four zones of groundwater availability that Conagua uses to classify Mexico's aquifers using a groundwater availability index ($GWAI$) [56, 72]. The $GWAI_i$ for each watershed is estimated using Equation 2.7:

$$GWAI_i = \frac{MAGWA_i}{R_i - NCD_i} \tag{2.7}$$

The ranges of the $GWAI$ used to classify the aquifers by zones are shown in Table 2.3. These zones are based on the WA in each aquifer in ascending order from Zone 1 to Zone 4 and are used to determine the water prices. As shown in Table 2.3, the price per cubic meter of water in the aquifers classified as Zone 1, Zone 2, and Zone 3 are 921%, 295%, and 38% more expensive than in Zone 4.

Table 2.3: Zones of groundwater availability and ranges of GWAI where the best zone is 4 and the worst is 1. Low numbers of the GWAI indicate more water scarcity.

Zone	Range of GWAI	Increase in water price with respect to Zone 4
Zone 1	GWAI < -0.1	921%
Zone 2	-0.1 > SWAI < 0.1	295%
Zone 3	0.1 > GWAI < 0.8	38%
Zone 4	GWAI > 0.8	-

The three different alternatives analyzed were:

- **Alternative 1.** This alternative evaluates the case in which all the GWA_i is supplied for HF in the intersection of the aquifers and the shale areas. Under this alternative, new water users could not be added, nor could current users increase their demand. Also, the water price for all users would be more expensive. This alternative provides an upper bound.

- **Alternative 2.** This alternative evaluates the case in which part of the GWA_i is supplied for HF, but leaving a $GWAI > 0.1$ (Zone 3). Under this alternative, new users could still be added or current users could increase their water demand, and the water price for all users would either remain the same or increase by around 38%.

- **Alternative 3.** This alternative evaluates the case in which part of the GWA_i is supplied for HF, but leaving a $GWAI > 0.8$ (Zone 4). Under this alternative, new users could still be added or current users could increase their water demand, and the water price for all users would remain in the cheapest price.

Equation 2.8 was used to determine the volume supplied for HF in the alternatives 2 and 3:

$$y_i = MAGWA_i - GWAI(R_i - NCD_i) \tag{2.8}$$

where y_i is the water available to be supplied from aquifer i by leaving a $GWAI$ greater or equal to 0.1 or 0.8, respectively. For the aquifers with saline water (brackish or marine intrusion) the fresh and saline water are lumped together in the $MAGWA$. In these aquifers, the water available for new water intensive users, such as HF, could increase since the demand for saline water is typically smaller than for freshwater. Future research has to be conducted to estimate specific availability of saline water in the aquifers overlaying the shale areas.

2.2.3 Water Availability

Three scenarios of WA, described in Table 2.4, for the shale areas in the shale basins were analyzed by intersecting the surface and groundwater availability alternatives.

Table 2.4: Three water availability scenarios were analyzed from the intersection of the different ground and surface water availability alternatives.

Scenario	Watershed final classification	Aquifer final classification	Description
Scenario 1	Zone 1	Zone 1	Estimates the WA after leaving the watersheds and aquifers classified as Zone 1 (Intersection of Alternatives 1). This means that no new user could be added or increase its demand, and the water price for all users would be the most expensive.
Scenario 2	Zone 3	Zone 3	Estimates the WA after leaving the watersheds and aquifers classified as Zone 3 (Intersection of Alternatives 2). This means more users could still be added or increase its demand, and the water price for all users would either remain the same or increase 30% to 38%.
Scenario 3	Zone 4	Zone 4	Estimates the WA after leaving the watersheds and aquifers classified as Zone 4 (Intersection of Alternatives 3). This means more users could still be added or increase its demand, and the water price for all users would be the cheapest.

2.3 Findings

The average annual WA was used to determine the EUR energy that could be extracted over the typical 20-30 year lifetime of the annual HF wells that could be supplied in the shale areas of the 5 shale basins in Mexico. For this first-cut analysis, the RR of the shale areas was treated as if it were evenly distributed. Also, it was assumed that the volume of water needed to extract the EUR of gas or oil would be in the same range as in the shale basins in the U.S., which is shown in Table 2.5.

Table 2.5: Range of water demand for HF in the different areas in the shale formations in the United States [4].

Areas	**Low Water Demand (gal/Quads)**	**Average Water Demand (gal/Quads)**	**High Water Demand (gal/Quads)**
Oil Areas	1.6×10^9	8.2×10^9	21.7×10^9
Gas Areas	1×10^9	5×10^9	28×10^9

2.3.1 Water Availability in the Burgos Basin

Figure 2.3 shows the EUR energy that could be extracted in the 3 scenarios analyzed in the shale areas of the Burgos Basin. The shaded areas represent the areas where at least 80% of the WA is located in each of the shale areas for each scenario. For instance, in Scenario 1 and 2 the WA is equally distributed in the oil area, whereas in Scenario 3 there is no WA at all in this area. For all the scenarios, the WA for the Oil, Wet Gas 1 (northern) and Dry Gas areas is from groundwater, while around 95% of the WA for the Wet Gas 2 area (southern) is from surface water. In Scenario 3, on average an EUR of around 6 Quads could be extracted in this basin while leaving the classification of the water sources in Zone 4. Most of this energy could be extracted in the wet gas area closer to the Gulf of Mexico (Wet Gas 2), and a fewer from the dry gas and northern wet gas areas.

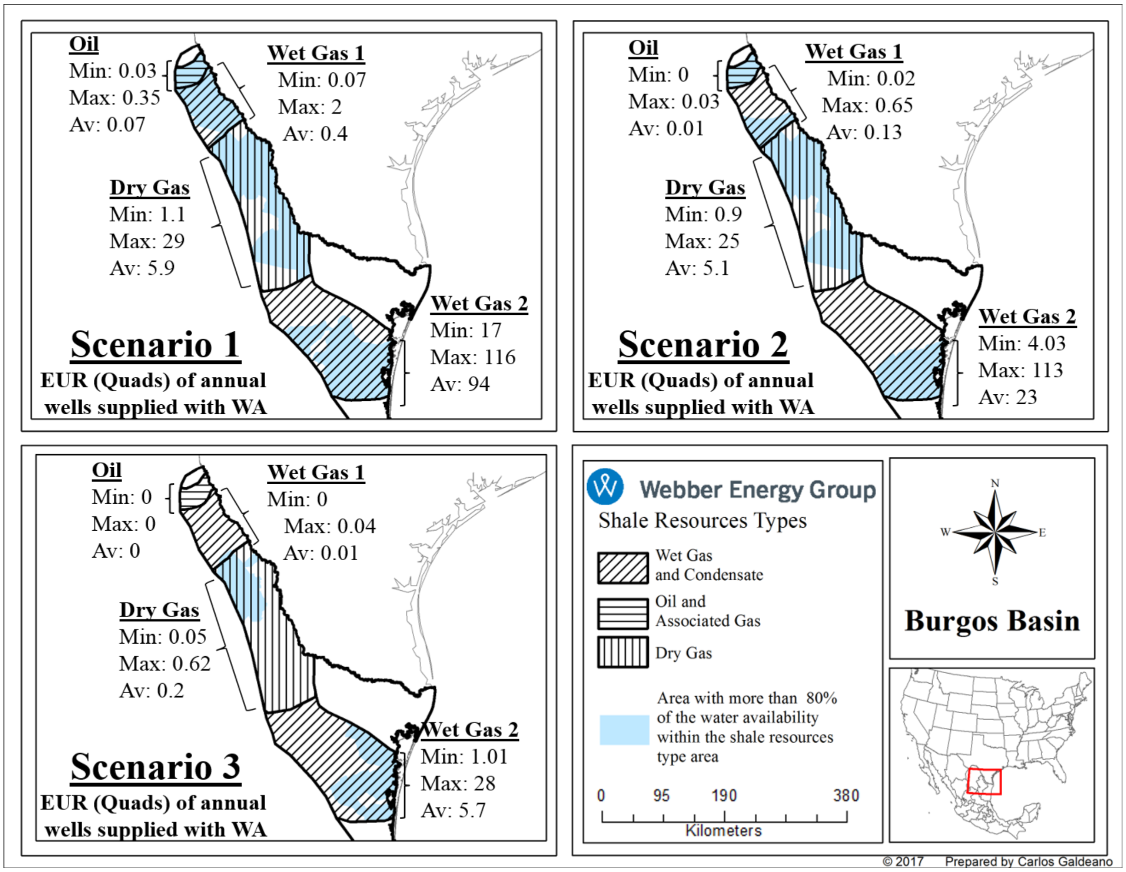

Figure 2.3: On average, Mexico could extract an EUR of around 100, 28, or 6 Quads over the lifetime of the wells that could be supplied with the average annual WA overlaying the Burgos Basin according to the scenarios analyzed (Scenario 1, 2, and 3 respectively).

2.3.2 Water Availability in the Sabinas Basin

Figure 2.4 shows the EUR energy that could be extracted in the 3 scenarios analyzed in the shale area of the Sabinas Basin. The shaded areas represent the areas where at least 80% of the WA is located in the Dry Gas area for each scenario. There is no surface water available in any scenario analyzed. In Scenario 3, on average an EUR of around 0.14 Quads could be extracted in this basin with the WA in the aquifers while leaving its classification as Zone 4.

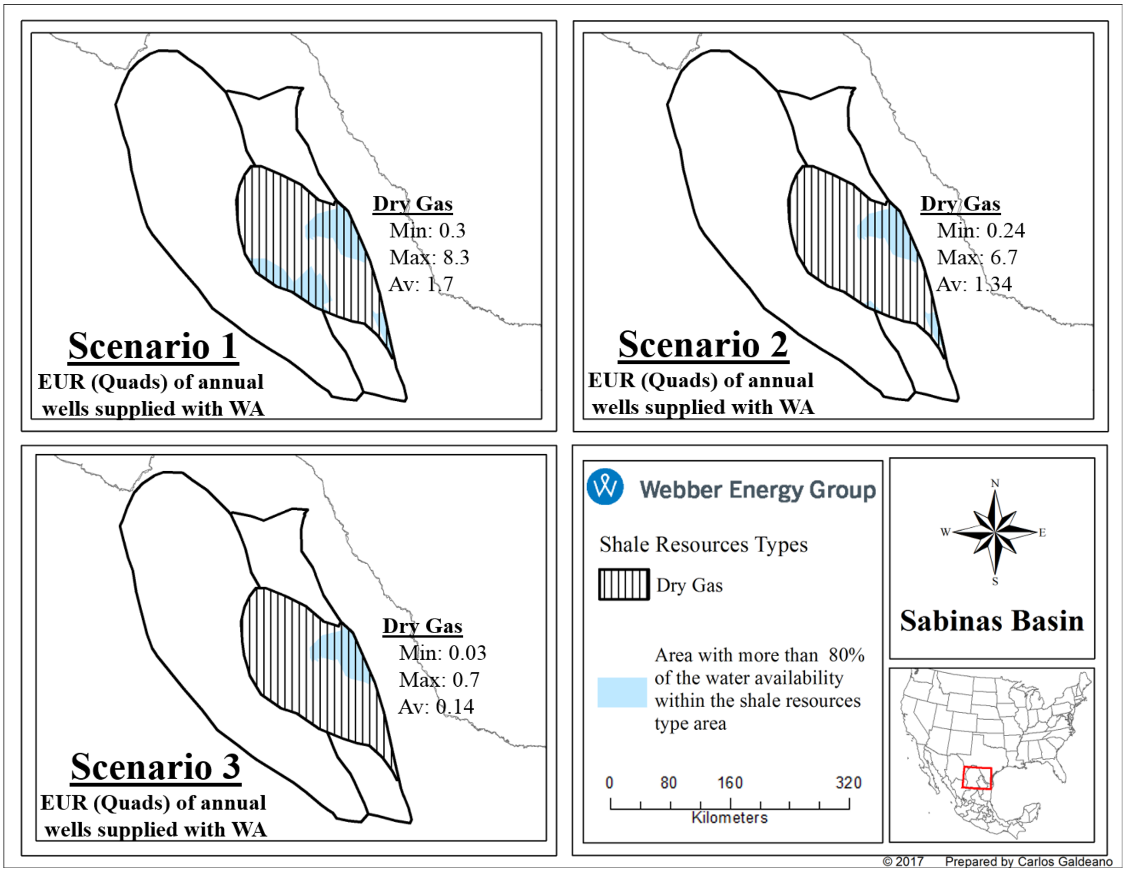

Figure 2.4: On average, Mexico could extract an EUR of around 1.7, 1.34, or 0.14 Quads over the lifetime of the wells that could be supplied with the average annual WA overlaying the Sabinas Basin according to the scenarios analyzed (Scenario 1, 2, and 3 respectively).

2.3.3 Water Availability in the Tampico Basin

Figure 2.5 shows the EUR energy that could be extracted in the 3 scenarios analyzed in the shale areas of the Tampico Basin. The shaded areas represent the areas where at least 80% of the WA is located in each shale area for each scenario. For Scenario 1, most of the WA is from surface water, while in Scenario 2 and 3 the main sources of water varies for each shale area (Table 2.6).

Table 2.6: The main source of water available for hydraulic fracturing in the Tampico Basins varies significantly in each scenario and for each type of shale resources area.

Scenario		Shale Resources Type Area		
		Oil	Wet Gas	Dry Gas
% of WA from surface water	Scenario 1	99%	99%	99%
	Scenario 2	83%	65%	72%
	Scenario 3	89%	71%	35%
% of WA from groundwa-ter	Scenario 1	1%	1%	1%
	Scenario 2	17%	35%	28%
	Scenario 3	11%	29%	65%

As Figure 2.5 shows, in Scenario 1 the maximum, minimum, and average EUR energy that could be extracted is the same in each shale area, which means that the average water that could be supplied to HF wells in one year could extract all the RR in these areas over the lifetime of these wells. In Scenario 3, on average an EUR of around 6 Quads could be extracted, while leaving the watersheds and aquifers classification as Zone 4. Most of this energy could be extracted in the Oil area closer to the Gulf of Mexico, followed by the Wet Gas and Dry Gas areas.

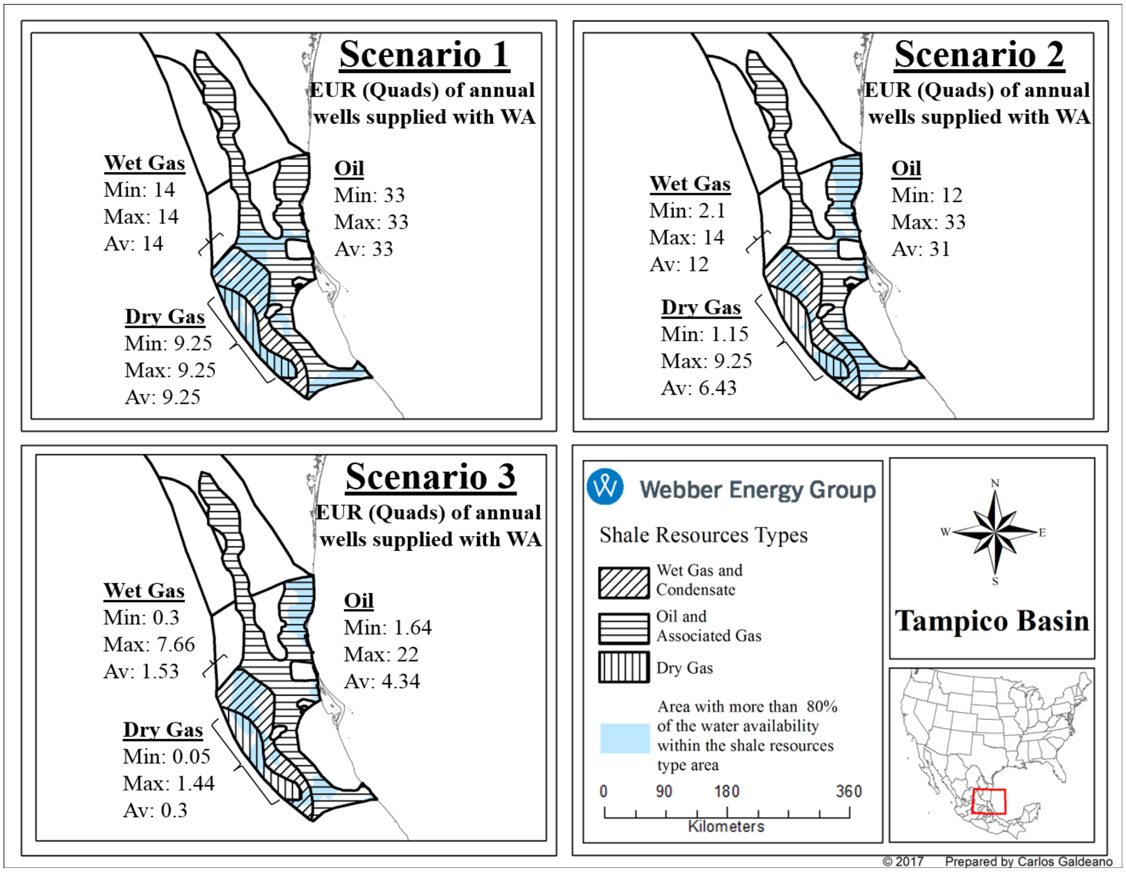

Figure 2.5: On average, Mexico could extract an EUR of around 56, 50, or 6 Quads in over lifetime of the wells that could be supplied with the average annual WA overlaying the Tampico Basin according to the scenarios analyzed (Scenario 1, 2, and 3 respectively).

2.3.4 Water Availability in the Tuxpan Basin

Figure 2.6 shows the EUR energy that could be extracted in the 3 scenarios analyzed in the different shale areas of the Tuxpan Basin. The shaded areas represent the areas where at least 80% of the WA is located for each scenario. For all the scenarios, more than 90% of the WA is from surface water. In Scenario 1, the maximum, minimum, and average EUR energy that could be extracted in the shale oil area of the Tuxpan Basin is the same, which means that the average water that could be supplied to the HF wells in one year could extract all the RR in these areas over the lifetime of these wells. In Scenario 3, on average an EUR of around 0.77 Quads could be extracted, while leaving its watersheds and aquifers classification as Zone 4.

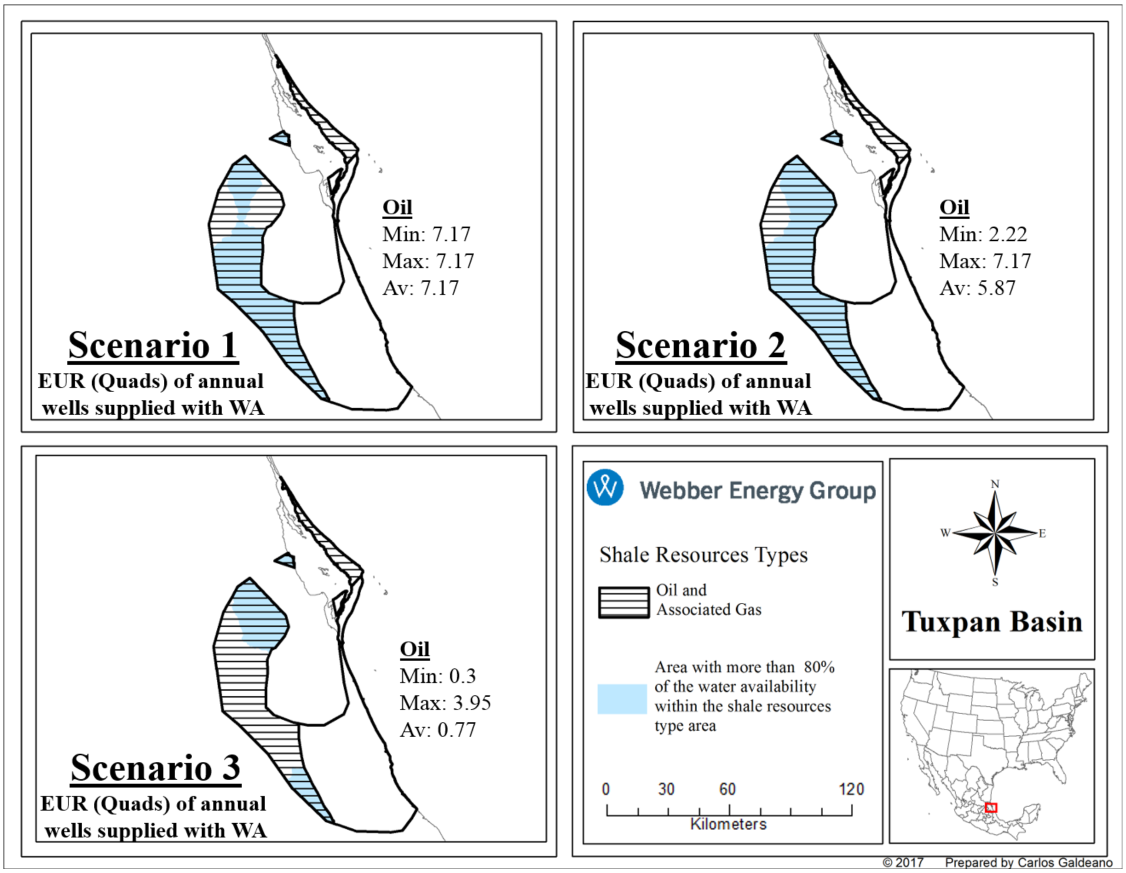

Figure 2.6: On average, Mexico could extract an EUR of around 7.2, 5.9, or 0.77 Quads over the lifetime of the wells that could be supplied with the average annual WA overlaying the Tuxpan Basin according to the scenarios analyzed (Scenario 1, 2, and 3 respectively).

2.3.5 Water Availability in the Veracruz Basin

Figure 2.7 shows the EUR energy that could be extracted in the 3 scenarios analyzed in the shale areas of the Veracruz Basin. The shaded areas represent the areas where at least 90% of the WA is located in each shale area for each scenario. For all the scenarios, more than 95% of the WA in both shale resources type areas (Oil and Dry Gas) is from surface water. In the 3 scenarios, the maximum, minimum, and average EUR energy that could be extracted is the same in each shale area, which means that the average water that could be supplied to the HF wells in one year could extract all the RR in these areas over the lifetime of these wells. The main reason is due to the high WA in the region and the small amount of RR located in these areas. Most of the water is located in the south of the shale areas.

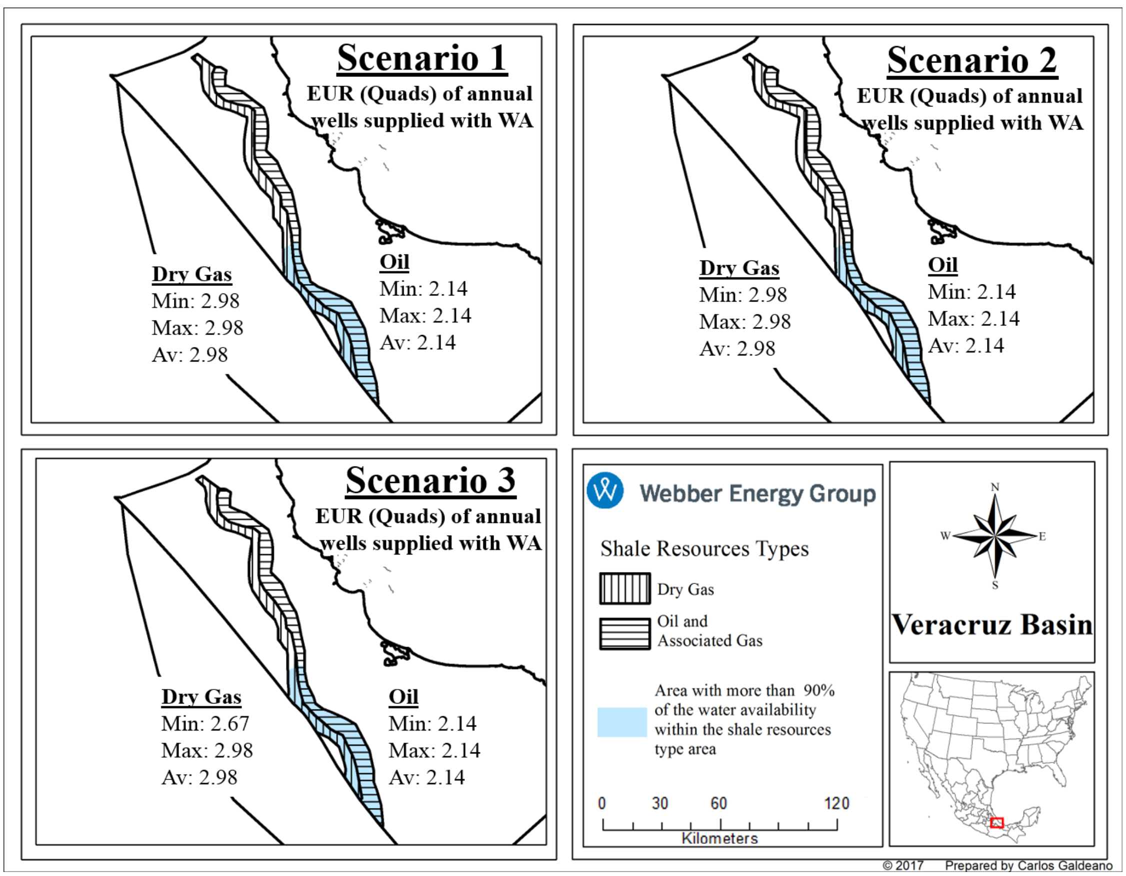

Figure 2.7: Mexico could extract all the risked technically recoverable resources (around 5 Quads) from the Veracruz Basin over the lifetime of the wells that could be supplied with the average annual WA according to all the scenarios analyzed (Scenario 1, 2, and 3).

2.4 Discussion

For the scenarios analyzed, WA varies along the five shale basins. In some cases there is more WA from surface water than for groundwater, and vice versa. This discussion is based on the results from Scenario 3, which estimates the amount of EUR energy that could be extracted while maintaining the WA indices of the aquifers and watersheds in the best classification possible (Zone 4). The WA estimated in Scenario 3 could be used to extract an EUR between 8.15 and 70.42 Quads, with an average of around 18.05 Quads (Table 2.7). The average EUR energy that could be extracted with the WA represents around 4% of Mexico's RR (around 440 Quads [2]). This average EUR energy would be extracted over the typical 20-30 year lifetime of the HF wells that could be supplied with the WA. This EUR energy would represents around 7% of Mexico's energy consumption in the next 30 years, assuming an annual energy consumption of around 7.5 Quads [73, 74].

Table 2.7: An EUR between 8.15 and 70.42 Quads, with an average of around 18.05 Quads, could be extracted leaving the watersheds and aquifers in their best corresponding classification (Zone 4).

Shale Basin	EUR energy that could be extracted with the WA in Scenario 3 (Quads)					
	Minimum		Average		Maximum	
	From watersheds	From aquifers	From watersheds	From aquifers	From watersheds	From aquifers
Burgos	0.99	0.06	5.54	0.32	27.70	1.62
Sabinas	0.00	0.03	0.00	0.14	0.00	0.71
Tampico	1.67	0.30	5.04	1.12	25.66	5.65
Tuxpan	0.28	0.01	0.75	0.02	3.83	0.13
Veracruz	4.80	0.01	5.11	0.01	5.11	0.01
TOTAL	**8.15**		**18.05**		**70.42**	

The geographic distribution of the WA varies across the shale areas in each shale basin, which could represent a challenge for extracting the RR. In the Burgos Basin, around 96.5% of the average EUR energy would be from the wet gas area closer to the Gulf of Mexico, representing about 4% of the RR of the combined wet gas areas in this basin (146 Quads [2]). The breakdown from the average EUR energy that could be extracted in this basin from the oil, northern wet gas, and dry gas areas was around 0%, 0.1%, and 3.4%, respectively. This energy represents about 0%, 0.005%, and 0.07%, of RR in the oil (6 Quads [2]), combined wet gas, and dry gas (288 Quads [2]) areas, respectively. The WA for the dry gas and northern wet gas areas would be from groundwater, whereas 98% of the WA for the wet gas area closer to the Gulf of Mexico would be from surface water.

In the Sabinas Basin, there is only groundwater available to extract dry gas in the northeastern area. The average EUR energy that could be extracted from this basin represents about 0.11% of its RR (127 Quads [2]). In the Tampico Basin, around 70%, 25%, and 5% of the total average EUR energy could be extracted from the oil, wet gas, and dry gas areas, respectively. This energy represents about 13%, 11%, and 3%, of the RR in the oil (32 Quads [2]), wet gas (14 Quads [2]), and dry gas (9 Quads [2]) areas, respectively. For the oil and wet gas areas of this basin, around 89% and 71% of the WA is from surface water, whereas for the dry gas area 65% of the WA is from groundwater. For the Tuxpan Basin, around 97% of the WA is from surface water. The average EUR energy that could be extracted from its oil area represents about 11% of its RR (7 Quads [2]). In the Veracruz basin, the EUR energy that could be extracted with the WA is equal to its RR (around 5.12 Quads [2]), which is due to the high surface water availability in the southern region of the shale basin.

2.5 Conclusion

Water availability varies across each of the five shale basins. Three scenarios were examined based on different impact level on watersheds and aquifers from HF. The most conservative scenario analyzed could assist to determine and identify the potential areas with WA for HF that would not increase water stress and water prices from the watersheds and aquifers overlaying the shale areas. Under this scenario, the average annual water available could be used to supply HF wells that can extract on average 18.05 Quads over a 20-30 year lifetime, which represents around 7% of the energy that Mexico is expected to consume in 30 years. However, the geographic distribution of the WA could represent a challenge for extracting the shale RR in some areas. Most of this water is located closer to the Gulf of Mexico; whereas the areas with less WA are in Northern Mexico, where the larger reserves are located. Future research has to be conducted to examine (1) a dynamic change in the spatial variables such as water demand growth of municipal and irrigation users, and (2) the water availability variation under extreme conditions (dry and wet years).

Chapter 3

Assessing potential reuse of produced water from hydraulic fracturing activity in prospective areas of the Burgos Basin (Mexico) across the Texas border

3.1 Introduction

The wastewater produced through HF is composed of drilling muds, flowback, and produced water (PW). Volumes and quality vary due to the characteristics of the shale formation and the process employed [36–38]. An increasingly common practice is to reuse the PW from HF to develop other HF wells, which addresses some of the environmental challenges associated with sourcing fresh water [75–80]. Therefore, it is relevant to develop a methodology to assess the potential reuse of PW in the unconventional areas listed in SENER's 5-year plan.

The main contribution of this chapter is to develop a methodology to forecast the potential PW from HF that could be reused to develop shale resources in water stress areas. In particular, this study centers on analyzing three unconventional areas expected to be developed in the Burgos Basin (Figure 3.1), which overlay the Rio Bravo/Grande transboundary basin. Furthermore, this chapter presents data, methodology, and results to identify potential oil and gas production through the reuse of the estimated PW as a water source for other HF wells. This research intends to provide a methodology that could assist policymakers in analyzing and implementing further regulations to include PW reuse as a water management strategy in the development of shale resources in Mexico.

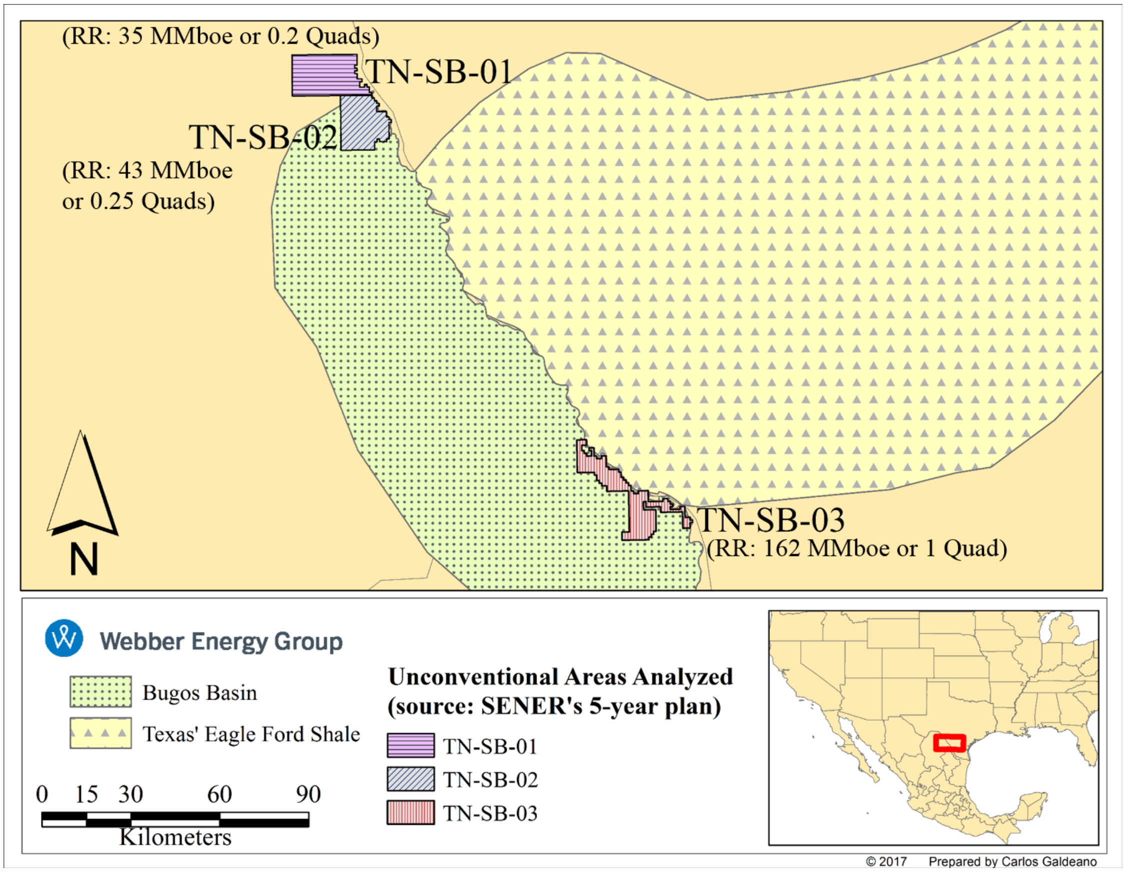

Figure 3.1: Two of the areas analyzed are located in oil areas (TN-SB-01 and TN-SB-02) with a combined RR of 0.45 Quads, while one area analyzed is located in a gas area (TN-SB-03) with a RR of 1 Quad.

3.2 Methodology

Table 3.1 shows the methodology used to estimate the potential PW to be extracted and potentially reused from HF in three prospective unconventional areas in the Burgos Basin. This methodology combines (1) a decline curve analysis of the PW from HF wells in the areas, (2) a drilling schedule forecast, and (3) a temporal analysis of the potential PW to be reused for HF in the areas analyzed.

Table 3.1: A decline curve analysis and a drilling activity forecast in 3 unconventional areas to be developed in the Burgos Basin was conducted to determine the potential PW to be extracted from HF in a 15-year period.

METHOD	OBJECTIVE	INPUT
1.Decline Curve Analysis of PW	Estimate the decline curves of the PW that could be extracted over time from HF wells in the three prospective areas in Burgos Basin	Time series of PW from the Texas' EFS HF wells (2014—2016) located across the border with Mexico [50]
2.Drilling Schedule Forecast	Forecast the HF drilling schedule in 3 unconventional areas to be developed in the three prospective areas in Burgos Basin	• HF wells drilled per year between 2010—2016 in Texas' EFS [50] • Water used per HF well in Texas' EFS from 2010—2016 [5] • Cumulative oil and gas extracted from HF wells in Texas' EFS from 2010—2016 [50]) • Recoverable reserves in the 3 areas analyzed in Burgos Basin [10]
3. Temporal Analysis of PW for Reuse	Estimate a time series of total PW that could be extracted in each of the three prospective areas in Burgos Basin, according to the drilling schedule forecast	• Estimated decline curves of PW in oil and gas areas in the EFS (from Decline curve analysis) • Schedule forecast of wells (normalized by water used and energy extraction) to be developed in the 3 areas analyzed in the Burgos Basin

3.2.1 Decline Curve Analysis of Produced Water

A decline curve analysis was conducted to determine the potential PW to be extracted per HF well drilled in the areas analyzed in the Burgos Basin. This analysis is commonly used in the oil and gas industry to forecast well production using real production data and empirical models [81–83]. Real PW production data from 2014 to 2016 of the HF wells in counties across the border from the Mexican states of Coahuila and Nuevo Leon in Texas' EFS were used to conduct the decline curve analysis. It was assumed that the characteristics of the EFS are similar across the border, which is reasonable due to the proximity of the HF wells used for the analysis with respect to the areas analyzed but more research is required to understand more precisely the characteritics of the shale formation in these areas. These data were obtained from the Drilling Info database [50], which includes the time series of oil, gas, and PW for each HF well. There are four empirical models commonly used to conduct decline curves analysis, which are (1) hyperbolic, (2) exponential, (3) harmonic, and (4) hyperbolic to exponential. These models were originally developed in 1945 by J.J. Arps [82]. Arps applied the hyperbola equations to forecast the decline production of conventional oil and gas wells, but this concept is still being applied to forecast production in unconventional wells [82, 83]. The empirical model that was used to forecast the production in each well was selected by minimizing the sum of square errors between the real production data of each well and the different empirical models [84].

- **Hyperbolic**. The hyperbolic model is the most general decline curve model [32]. The production rate (q) at each time on a hyperbolic model is estimated using Equation 3.1:

$$q = \frac{q_i}{(1 + b d_i t)^{\frac{1}{b}}} \tag{3.1}$$

  where q_i is the initial production rate, d_i is the nominal decline rate, t is the cumulative time since the initial production, and b is the hyperbolic decline constant, which ranges from 0 to 1.

- **Exponential**. The exponential model is considered the most conservative decline curve model [32]. This model is a special case of the hyperbolic formulation in which b is considered to be equal to 0. The production rate (q) at each time step on an exponential model is estimated using Equation 3.2:

$$q = q_i e^{-d_i t} \tag{3.2}$$

- **Harmonic**. The harmonic model is another special case of the hyperbolic formulation in which b is considered to be equal to 1 [82]. The production rate (q) at each time step on an exponential model is estimated using Equation 3.3:

$$q = \frac{q_i}{(1 + d_i t)} \tag{3.3}$$

- **Hyperbolic to exponential**. In some cases, a hyperbolic decline model might overestimate the production rate later in time; hence, the decline can be converted to an exponential decline at some point in time [82].

Figure 3.2 shows the annual distribution of the PW production obtained in the decline curve analysis with 2014—2016 Texas' EFS HF wells across the Mexican border. The first and third quartiles (Q1 and Q3, respectively), are used as range of the potential PW decline curves per well throughout a 15-year period to consider the inherent uncertainty from the decline curve analysis. The cumulative potential PW for the Q1 and Q3 in this period is 1.78 and 4.9 million gallons per well (Mgal/well), respectively.

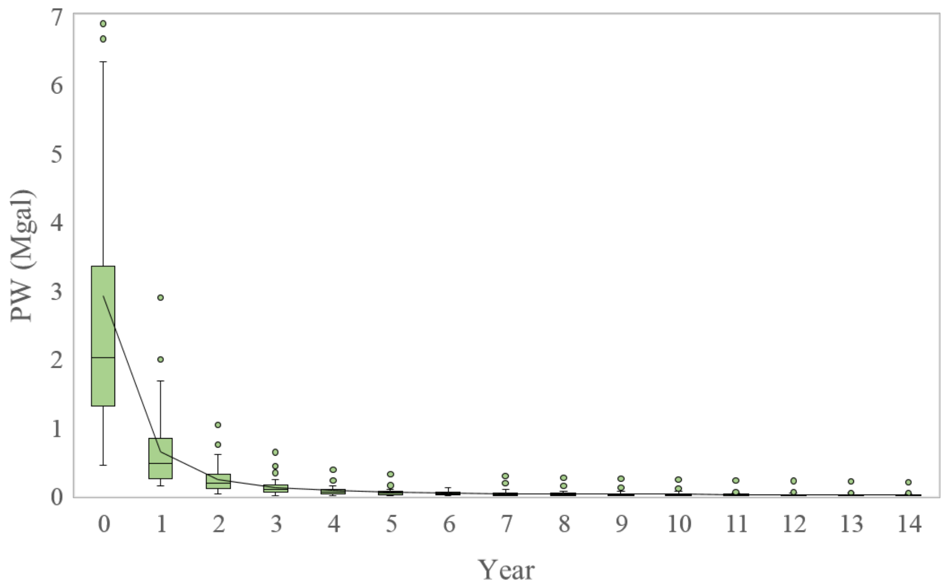

Figure 3.2: The first and third quartiles (Q1 and Q3) of the estimated decline curves from the 2014—2016 Texas' EFS HF are used as a range to estimate the potential PW to be extracted from HF in the three areas analyzed in the Burgos Basin.

3.2.2 Drilling Schedule Forecast Analysis

A forecast of a potential drilling schedule for each area was estimated to determine the potential number of wells to be developed in the areas analyzed. First, a time series of the number of wells was determined using the annual count of HF wells in Texas' EFS in a 7-year period (2010—2016), which was obtained from the Drilling Info database [50]. The time series was normalized by the average water withdrawal per well in the year in which the wells were developed to reflect the increase in water use due to changes in the HF process (e.g. longer laterals, different proppants, or different additives). Table 3.2 shows the increase in water use in Texas' EFS HF wells from 2010 to 2016 obtained with data from FracFocus database [5]. Finally, a drilling schedule in each area is forecasted (Figure 3.3) by normalizing the prospective RR with respect to the cumulative resources extracted through HF in the Texas' EFS (around 22 Quads). The cumulative extracted resources were obtained from Drilling Info database [50].

Table 3.2: The water used per HF well in Texas' EFS has been increasing from 2010 to 2016 due to modifications of the HF process [5], although the productivity of energy extracted per well has also been increasing [6, 7].

Year	**Water used for HF in EFS (Mgal/well)**			
	Q1	**Average**	**Median**	**Q3**
2010	1.83	3.37	3.33	4.82
2011	3.18	3.90	3.71	4.50
2012	3.25	4.61	4.16	5.60
2013	3.36	5.16	4.66	6.65
2014	4.34	6.47	5.99	8.05
2015	5.10	7.74	7.06	9.71
2016	6.03	8.77	7.78	11.00

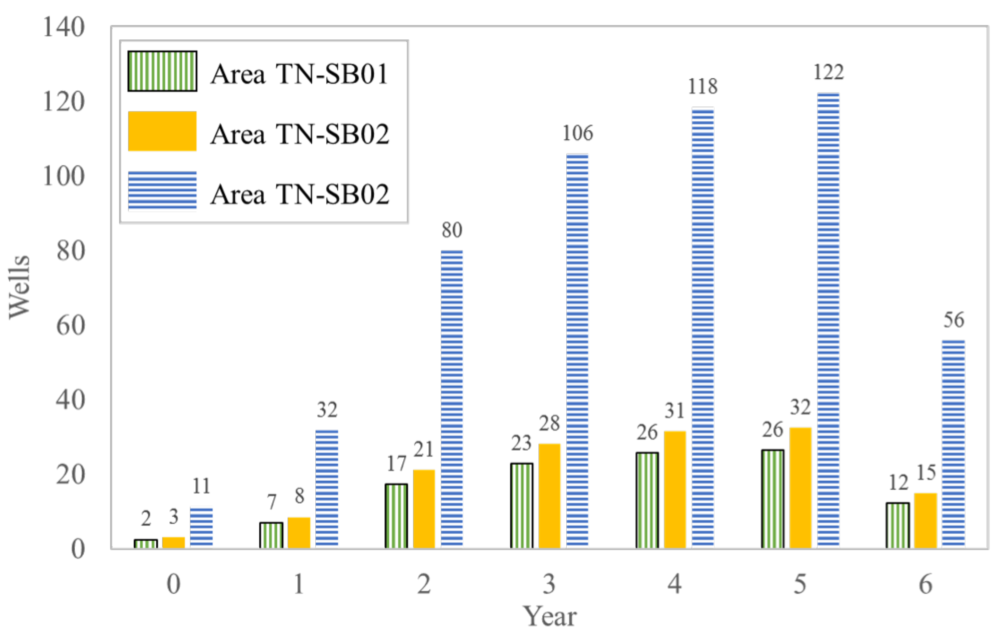

Figure 3.3: Drilling schedule forecast for the three areas estimated by normalizing the number of wells drilled in Texas' EFS by (a) the volume of water required per well in each year with respect to the volume required in 2016, and (b) the RR in each area with respect to the RR in Texas' EFS.

3.2.3 Temporal Analysis of Produced Water for Reuse

The temporal analysis of PW for reuse in the three unconventional areas analyzed was conducted using (1) the ranges of the annual PW over time expected in the three prospective areas in Burgos Basin in the decline curve analysis, and (2) the normalized drilling schedule forecast. The total annual volume of PW expected in the areas analyzed in a 15-year period was estimated using Equation 3.4:

$$PW_t = \sum_{i=0}^{t} w_i \left(V_{\frac{PW}{well}} \right)_{t-i} \tag{3.4}$$

where PW_t is the produced water in year t of the 15-year period analyzed (0 to 14), w_i is the normalized number of wells in each year (i) to be completed according to the forecasted drilling schedule, $V_{\frac{PW}{well}}$ is the volume of PW per HF well at each time step.

3.3 Findings and Discussion

Figure 3.4 shows the potential range of PW to be extracted from HF activity in a 15-year period in the three unconventional areas analyzed (TN-SB-01, TN-SB-02, and TN-SB-03). The estimated PW in the oil areas (TN-SB-01 and TN-SB-02) are alike due to their similar prospective RR volumes (0.2 and 0.25 Quads, respectively). Alternatively, the estimated PW in the gas area analyzed (TN-SB-03) is around 5 times larger than in the oil areas due to its higher prospective RR volume (1 Quad). In the three areas, the PW peak would happen in year 6. The peak production in these areas (TN-SB-01, TN-SB-02, and TN-SB-03) would range from 45 to 119 Mgal, 55 to 146 Mgal, and 208 to 550 Mgal, respectively.

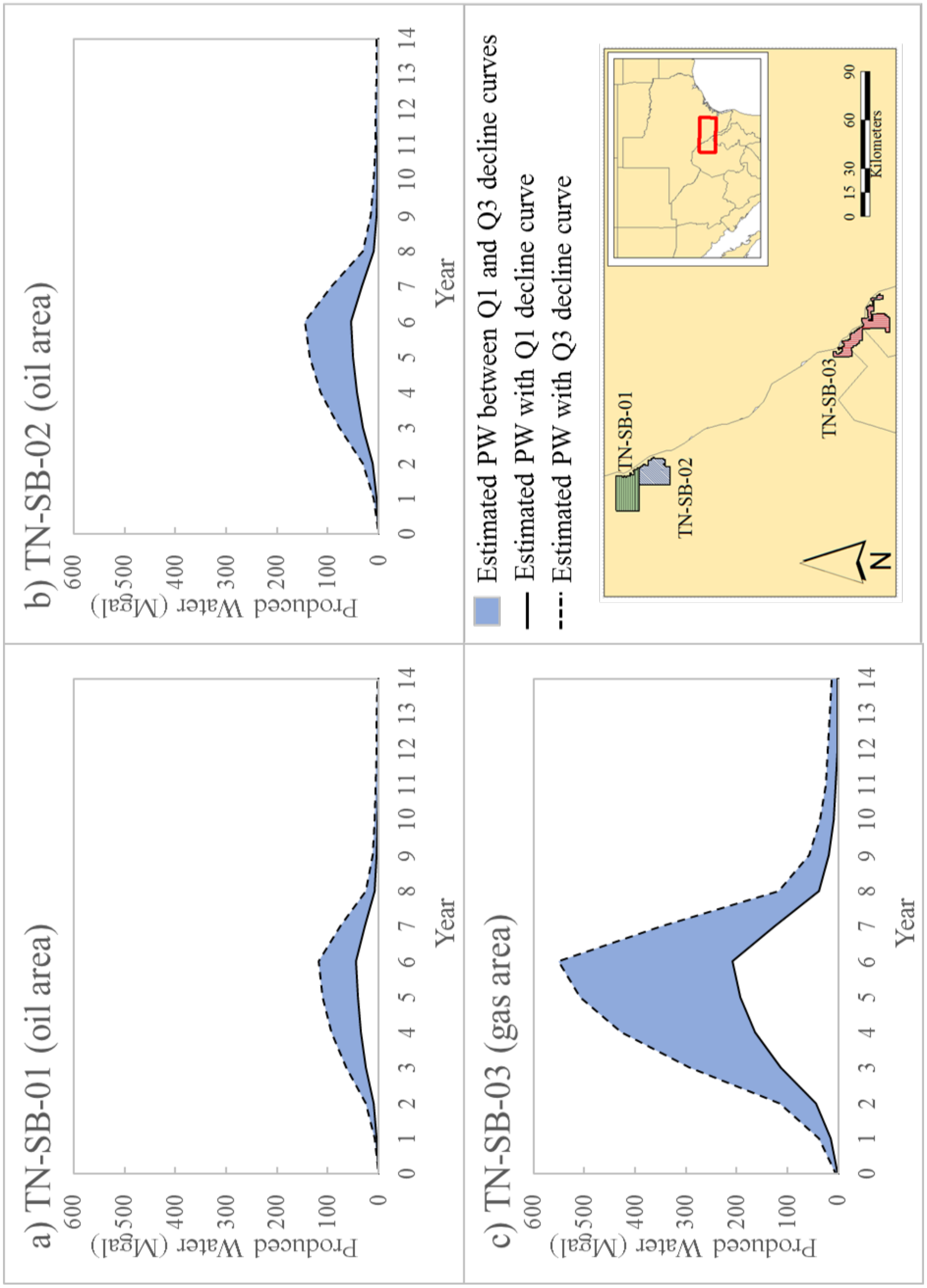

Figure 3.4: The PW to be extracted from HF activity is 5 times larger in the gas area analyzed (TN-SB-03) than the oil areas (TN-SB-01 and TN-SB-02).

Table 3.3 shows the cumulative PW in the 15-year period for each area analyzed. The total PW from these areas ranged from 1.39 to 3.81 billion gallons (Bgal). Around 67.5% of this PW would be extracted in the gas area TN-SB-03, while around 15% and 17.5% of the PW would be extracted in the oil areas (TN-SB-01 and TN-SB-02, respectively).

Table 3.3: The total cumulative PW in the 3 areas combined would range from 1.39 to 3.81 Bgal in the 15-year period analyzed.

Unconventional Area	**Cumulative PW (Bgal)**	
	Using Q1 PW decline curve	**Using Q3 PW decline curve**
TN-SB-01	0.20	0.56
TN-SB-02	0.25	0.68
TN-SB-03	0.94	2.57
TOTAL	**1.39**	**3.81**

According to data from FracFocus [5], in 2016 HF wells in Texas' EFS used on average 8.77 Mgal/well (Table 3.2). This water used per HF well and the average oil and gas production in a 20-year period from HF wells in the Texas' EFS (Figure 3.5), were used to estimate the annual energy that could be extracted in 20 years reusing the potential PW (Figure 3.4).

Figure 3.6 shows the energy that could be extracted in each area analyzed by reusing the estimated annual PW available as a water source for other HF wells. The PW is assumed to be of an adequate quality for reuse, but more research needs to be conducted to determine the required treatment for reuse in addition to the losses associated with that required treatment. In the 20 years analyzed, the cumulative energy production with the reused PW in the studied areas (TN-SB-01, TN-SB-02, and TN-SB-03) would range from 11 to 29, 13 to 35, and 36 to 94 Trillion BTUs, respectively. The peak energy production with the reused PW would occur around year 6 for the oil areas (TN-SB-01 and TN-SB-02) and would occur around year 5 for the gas area (TN-SB-03). Peak production would range from 1.3 to 3.5, 1.6 to 4.3, and 5.9 to15.2 Trillion BTUs, respectively.

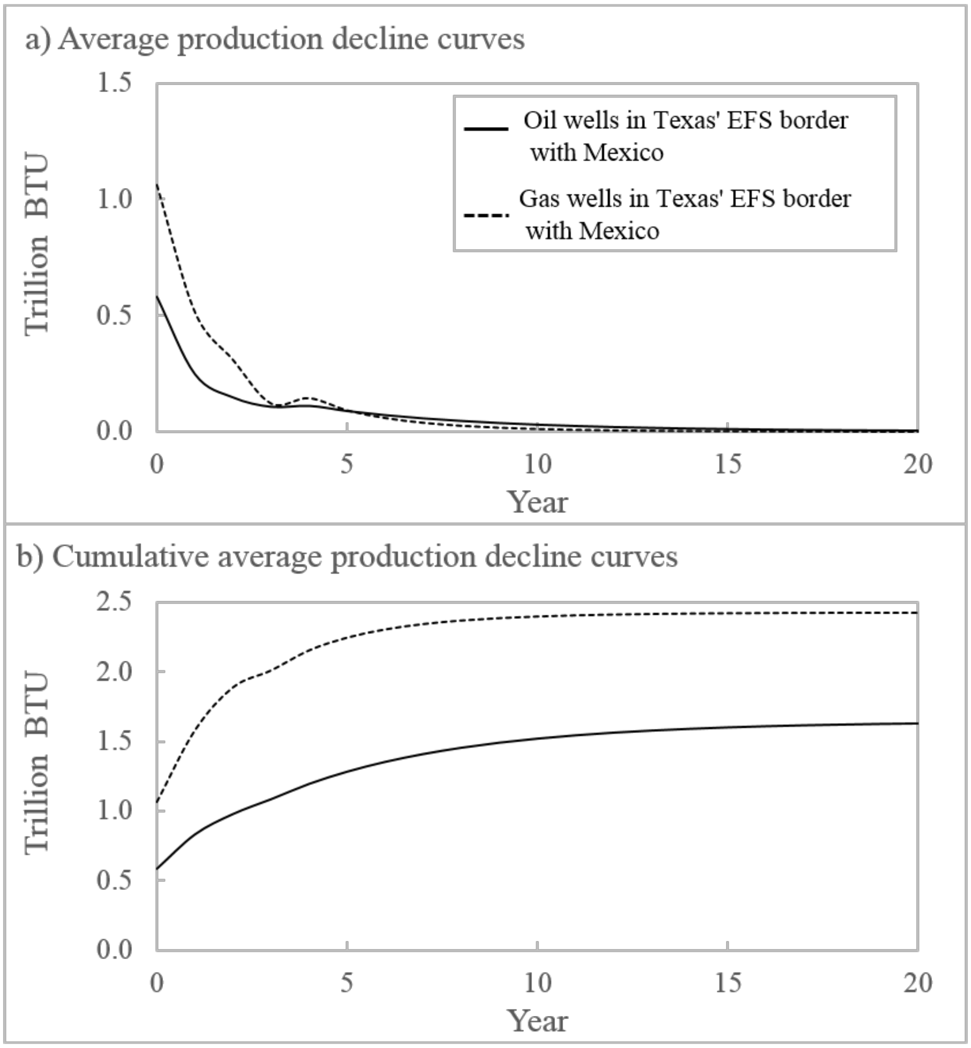

Figure 3.5: On average, the cumulative energy production in a 20-year period of 2014—2017 HF wells in Texas' EFS across the Mexican border is 1.63 Trillion BTUs for oil areas, and 2.42 Trillion BTUs for gas areas.

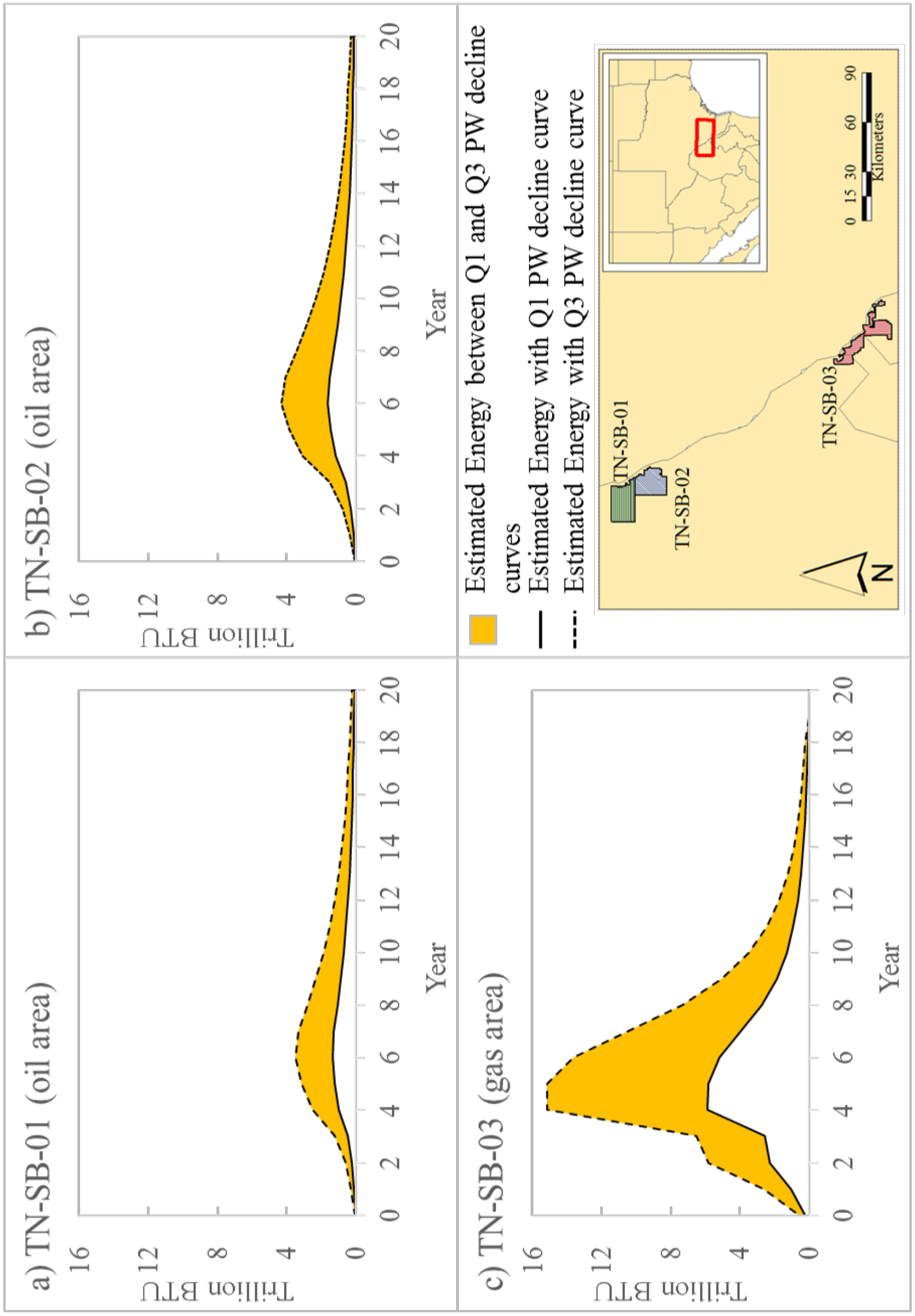

Figure 3.6: The energy production would peak in year 6 for the oil areas (TN-SB-01 and TN-SB-02) ranging from 1.3 to 3.5 and 1.6 to 4.3 Trillion BTUs, and in year 5 for the gas area (TN-SB-03) ranging from 5.9 to 15.2 Trillion BTUs.

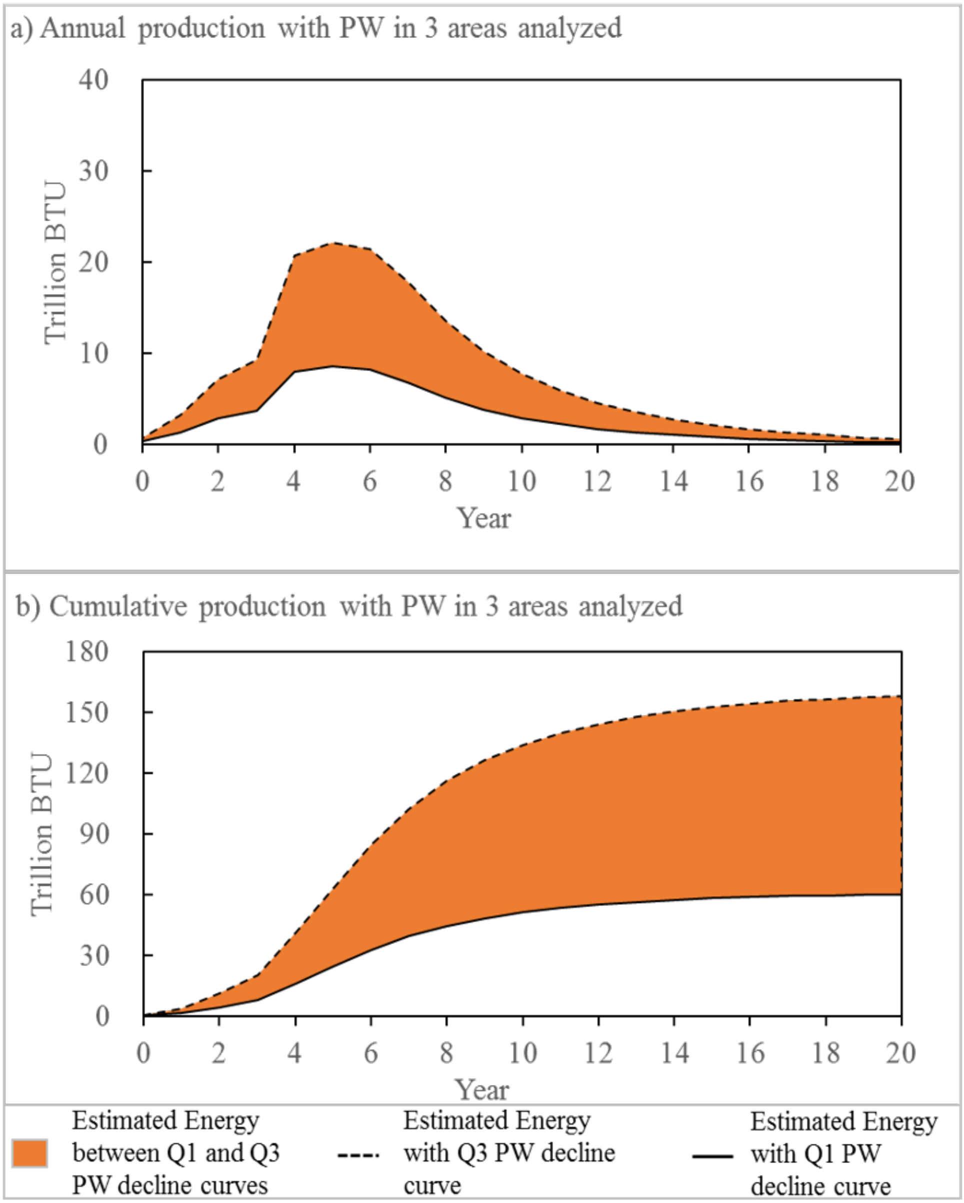

Figure 3.7: The potential annual energy production of the 3 areas combined peaks in year 5 and ranges from 8.5 to 22.2 Trillion BTUs, while the total cumulative energy production in a 20-year period ranges from 60 to 158 Trillion BTUs.

Figure 3.7 shows the total annual and cumulative energy that could be extracted by reusing the estimated annual PW from the three areas combined for other

HF wells. In the 20 years analyzed, the total cumulative energy production with the reused PW would range from 60 to 158 Trillion BTUs, from which TN-SB-01, TN-SB-02, and TN-SB-03 would contribute in 18%, 22%, and 60% respectively. Peak energy production with the reused PW would occur around year 5 and would range from 8.5 to 22.2 Trillion BTUs, representing between 0.1%—0.3% of Mexico's annual energy consumption, assuming continued annual consumption of 7,500 Trillion BTUs/year [73, 74].

3.4 Conclusion

The produced water from hydraulic fracturing wells is estimated to vary depending on different factors such as of shale formation characteristics and process employed [36, 37]. A range of potential PW per HF well in a 15-year period was estimated using the quartiles 1 and 3 of a decline curve analysis, conducted using data from 2014—2017 of HF wells in Texas' EFS across the Mexican border. A drilling schedule was forecasted for three prospective areas in Mexico's Burgos Basin (included in SENER's 5-year development plan [10]) by using the annual Texas' EFS well count from 2010 to 2017. The schedule was normalized by (1) the annual change in water used per well in the Texas' EFS, and (2) the prospective resources in the three areas analyzed with respect to the cumulative shale resources extracted in Texas' EFS.

The estimated PW from the development of the prospective areas analyzed could be used to supply other HF wells. These HF wells could produce between 60 to 158 Trillion BTUs of oil and gas throughout a 20-year period, peaking in production in year 5 at around 8.5 to 22.2 Trillion BTU, or 0.1%—0.3% of Mexico's annual energy consumption [73, 74]. More research needs to be conducted to understand the specific characteristics of the shale formations in the region. Furthermore, the analysis conducted in this research does not include any economic considerations, and future research should also analyze (a) the quality of the PW in the prospective areas analyzed, (b) the treatment required for reuse in other HF wells, (c) the volume losses derived from the treatment required, and (d) the costs associated with the treatment and management of the produced water and brine waste from the treatment required.

Chapter 4

Evaluating increase in water availability for current and potential new users from shifting two coal power plant for a natural gas combined cycle in the middle Rio Grande/Bravo

4.1 Introduction

Despite the additional water use for producing natural gas with HF in Texas, it was found that replacing conventional coal-fired power plants with new, natural gas-fired combined cycle power plants would reduce water consumption overall because of reduced water use for cooling power plants [54, 85]. Two Mexican coal-fired power plants (Jose Lopez Portillo (JLP) and Carbon II (CII)), located between the Amistad and Falcon dams, overlay the oil area in the Burgos Basin and have a water right of 47.5 million cubic meters per year (Mm^3/year) diverted from the RGB mainstream (Figure 4.1). According to data from Mexico's Department of Energy [86, 87], these power plants have a combined installed capacity of 2,600 MW and generated 16,388 GWh in 2016, representing about 7% of the total electricity generated in Mexico in that year. The water withdrawal by these power plants is diverted 30 kilometers from the RGB and stored in a local reservoir [88].

The main contribution of this chapter is to develop a methodology to assess the potential changes in water availability in a water stressed basin due to a shift of current energy production facilities to more water efficient energy sources (from coal to gas) and power plant technology (from steam cycle to combined cycle) in the region. This study considers the transboundary RGB basin as a case study due to (1) the geographic location of the Burgos Basin, (2) the existing water stress due to over allocated water rights in the RGB basin, and (3) the presence of two Mexican coal-fired power plants that withdrawal water from the middle RGB and are overlaying the oil area of the Burgos Basin. It is hypothesized that changing the current energy production facilities from coal-fired steam power plants (CPPs) to natural gas combined cycle (NGCC) will generate water savings and thus, increase water available to either current users (irrigation districts) or new users (HF sites).

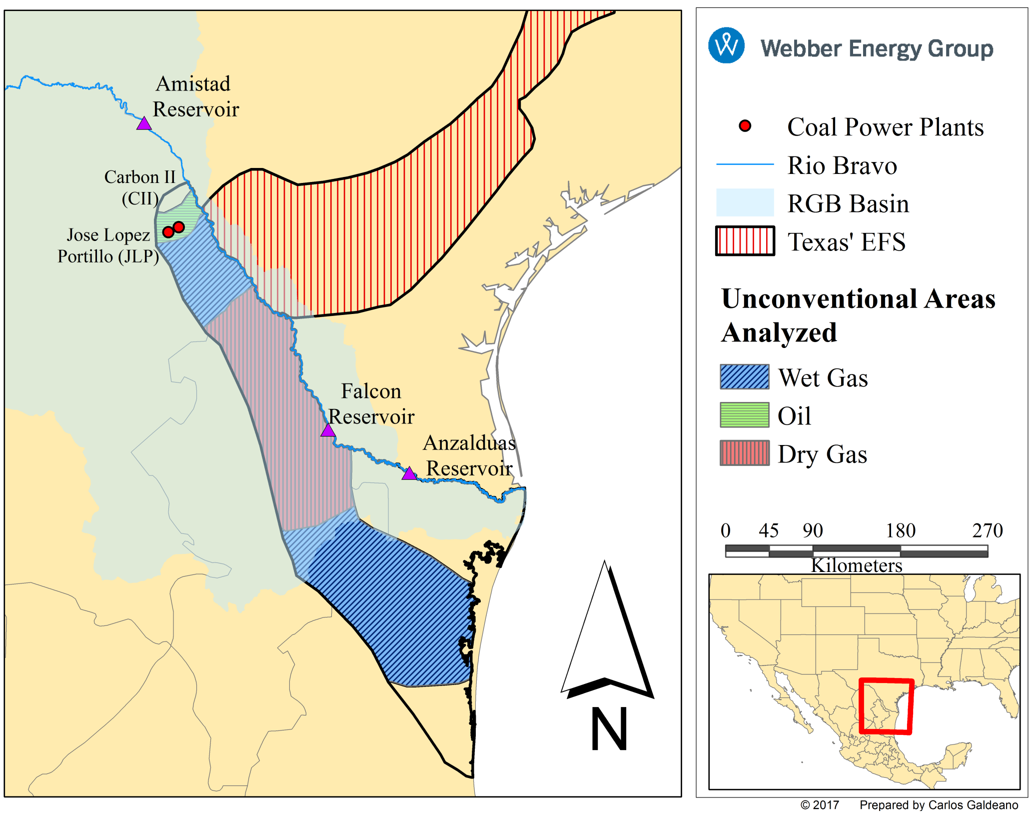

Figure 4.1: The RGB Basin overlays the Eagle Ford Shale Formation and Burgos Basin, and provides water to the two coal-fired power plants in the Northern Mexico (Jose Lopez Portillo and Carbon II).

4.2 Methodology

The methodology employed to assess the potential changes in water availability in the RGB due to a shift of two current CPPs for a NGCC is shown in Figure 4.2. A water allocation model of the RGB basin, developed in the Center for Research in Water Resources (CRWR) at The University of Texas at Austin [89], was coupled with a water demand calculator that takes into account changes on water demand for energy production. The water calculator was developed to modify the water allocation model for potential water management scenarios triggered by Mexico's energy reform. The following four scenarios were simulated and analyzed after coupling these two models:

1. Baseline Scenario: Normal water allocation over years 1940 to 2000.

2. Scenario 1: The CPPs were substituted with a single NGCC that would generate the same amount of electricity as the original CPPs. The baseline water right of the CPPs (about 47.5 Mm^3/year) was decreased to match the water demand needed by a NGCC (assuming a wet closed-loop cooling system). Water savings were not re-allocated.

3. Scenario 2: Similar to Scenario 1, but the water savings were sold to one of the irrigation districts (DR050, DR026 and DR025) located in the Mexican side of the border downstream from Amistad Dam.

4. Scenario 3: Similar to Scenario 1, but the water savings were sold to HF sites in the nearby area.

The reliability, resilience, and vulnerability parameters of the water supplied to the (1) power plants, (2) irrigation districts, and (3) HF sites were estimated and analyzed. In addition, the annual average extra revenues were estimated for each alternative of selling water to an irrigation district in Scenario 2, and the potential annual average number of wells that could be supplied for HF was estimated in Scenario 3. With the addition of HF users in the region, there will also be increases in water demand for workers moving to the area. In Scenario 3, this additional domestic water use was subtracted from available water for HF. Finally, an economic analysis was conducted to identify the breakeven prices at which the sales of the water savings plus the changes in operational and fuel costs would offset the initial investment.

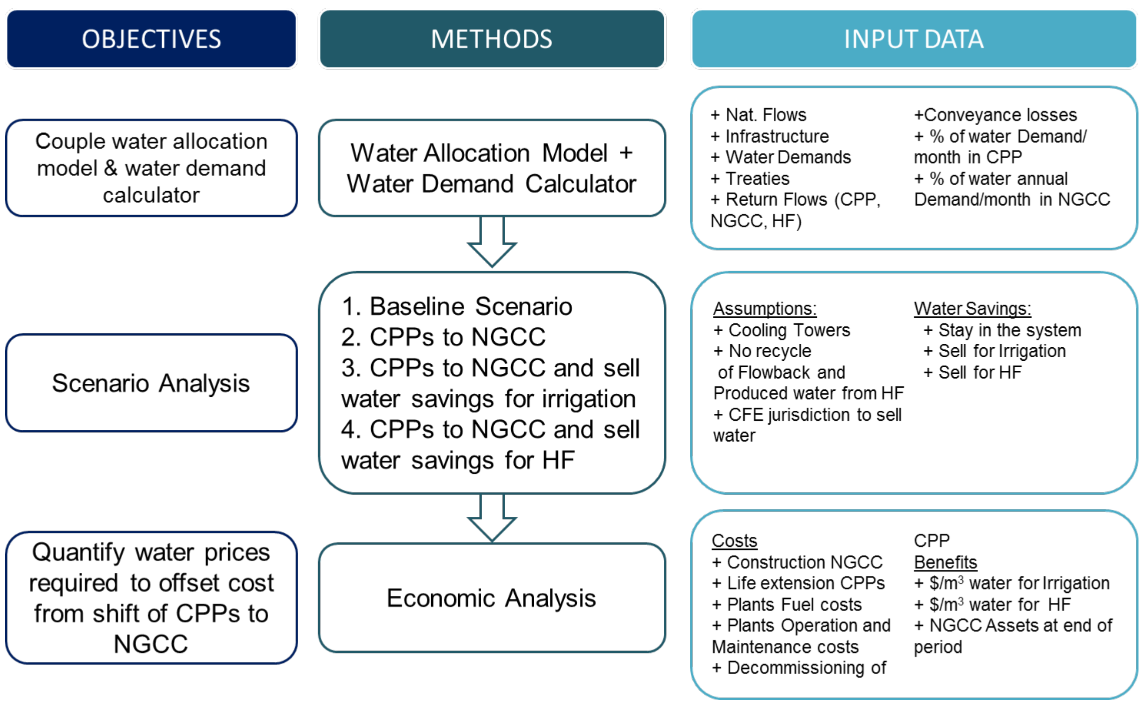

Figure 4.2: The potential water availability effects of Mexican energy reform in the RGB basin were quantified using this methodology.

4.2.1 Water Allocation Model and Power Plant Water Demand Calculator

Water Allocation Model (WEAP Model)

The RGB WEAP model (Figure 4.3) was built using the Water and Evaluation and Planning (WEAP) platform [59]. This platform is a simulation environment developed by the Stockholm Environment Institute that has an embedded linear program that solves allocation equations based on water demand priorities [90]. WEAP works on the basic principle of water balancing accounting with prioritized water demand sites linked to water supplies from rivers, reservoirs, and aquifers [60]. The water supplies for the RGB were generated by hydrologic data obtained from a geodatabase created as a joint effort between the CRWR, Texas Commission on Environmental Quality (TCEQ), Conagua, and the Mexican Institute of Water Technology (IMTA) [91]. A monthly series of naturalized flows for a 60 year period (1940—2000) were estimated for the RGB and its major tributaries using data from TCEQ [92]. This naturalized flow data series include the losses due to channel seepage, evaporation, and evapotranspiration [60].

The water demand sites include municipal, irrigation, industrial, and other users. All the demand sites in the RGB WEAP model have a water right assigned with a priority level. Due to the large number of users, water demands for the lower basin on the Texas side were aggregated in the model into larger demand sites based on their type, location, and legal jurisdiction [89]. The model delivers water to sites with first priority, followed by users with second priority, and so on. In addition to priority for allocation, WEAP allows scripting to create rules for a basin based on treaties and operational criteria of reservoirs. In this case, the 1906 Convention [63], the US-Mexico 1944 Treaty [64], the Interstate Compacts for the Rio Grande (Colorado, New Mexico, and Texas), the Texas Watermaster rules for Texas water rights [93], and the rules for tracking the Mexican and U.S. water accounts in the two international reservoirs (Falcon and Amistad) were included in the RGB WEAP model [60].

The RGB WEAP model was calibrated by adjusting some parameters to achieve results closer to the historical conditions of the basin. After being calibrated, the model was validated by first entering known historic water demands into the model for a 15 year period (1978 to 1992), and then comparing the modeled and historical storage values of the U.S. and Mexican accounts in the Falcon and Amistad reservoirs [60]. The differences between the modeled and historical storage values were 3.6% and 4.3% respectively for the Mexican and U.S. accounts, which corroborated that the RGB WEAP model runs a reasonable simulation of the water management in the RGB basin [60].

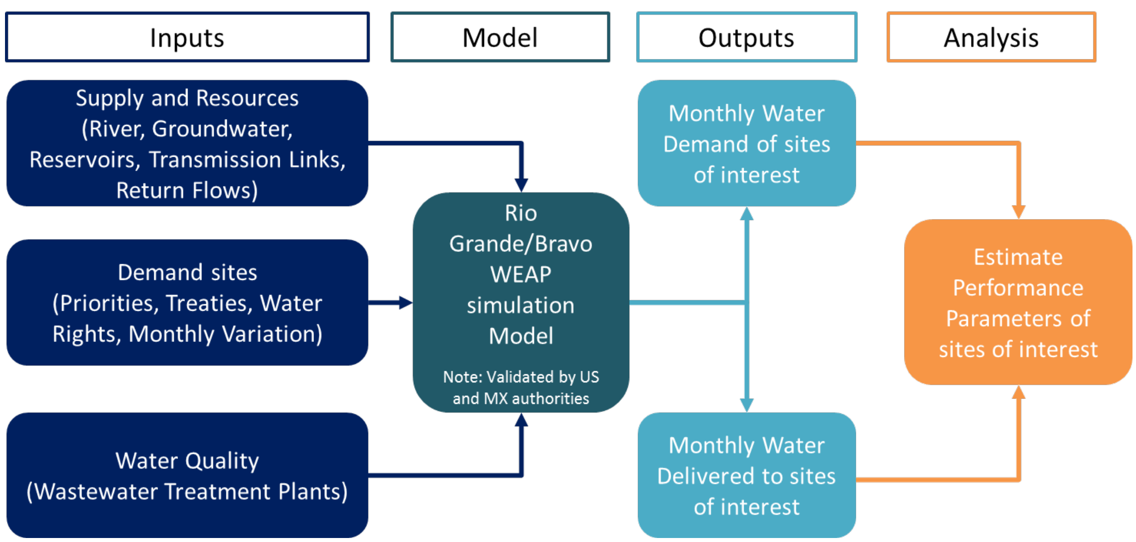

Figure 4.3: The RGB WEAP model showing inputs and outputs. The outputs were used to estimate the performance parameters for each of the scenarios simulated.

Water Demand Calculator for Energy Production

The water demand calculator was developed to determine the (1) annual water withdrawal required by the NGCC that could replace the CPPs, (2) percentage of annual water demand per month in the CPPs and a NGCC, (3) return flows of the HF sites (flowback and produced water), (4) return flows of the CPPs and NGCC, (5) conveyance losses from the power plant location to the irrigation districts (DR025, D026, and DR050), and (6) annual water demand of people moving to the region due to HF development. The annual water withdrawal of the NGCC was estimated using 2014—2015 data of NGCC power plants with cooling tower in Texas published by the U.S. Energy Information Administration (EIA) [94, 95]. Due to the different sources of uncertainty related with the water withdrawal required by the NGCC, the upper and lower boundaries of a 95% confidence interval was used to analyze a low and a high water demand alternative (Low WW and High WW).

The percentage of annual water demand per month in the CPPs and a NGCC were estimated using data published by the EIA [94] of power plants with similar characteristics in Texas. The return flows of the HF sites (flowback and produced water) were considered to be similar to those in the EFS formation in Texas (20% [52, 53]) and were assumed to be deep well injected. Deep well injection is a common produced water management practice in HF, but further research needs to be conducted to determine if this practice is feasible in the area analyzed. The return flows of the CPPs and NGCC were estimated using the average water consumption and withdrawal at Texas' power plants [96]. The conveyance losses were estimated with the channel loss factors for the river reaches previously estimated in the WEAP model [58]. The water demand of people moving to the region due to HF development was calculated assuming that the jobs per HF well would be similar to what happened in the Texas'

EFS region [97].

4.2.2 Scenario Analysis

The results from the water demand calculator were used to modify the WEAP model to simulate potential scenarios that could be triggered by Mexico's energy reform. Once the water demand calculator was coupled with the water allocation model, the four scenarios described below were simulated.

Baseline

This scenario establishes the baseline by running the WEAP model with historic conditions. The water right of the CPPs (WR_{CPPs}) was equal to their water demand (WD_{CPPs}). The return flow of the CPPs (RF_{CPPs}) was estimated with Equation 4.1:

$$RF_{CPPs} = 1 - \frac{\left(\frac{W_{consumed}}{kWh_{generated}}\right)_{forCPPs}}{\left(\frac{W_{withdrawal}}{kWh_{generated}}\right)_{forCPPs}} \tag{4.1}$$

where $\left(\frac{W_{consumed}}{kWh_{generated}}\right)_{forCPPs}$ and $\left(\frac{W_{withdrawal}}{kWh_{generated}}\right)_{forCPPs}$ are the water consumption and withdrawal of the CPPs, which were assumed to be analogous to a similar coal power plant with closed-loop cooling system in Texas.

Scenario 1

In this scenario, it was assumed that the CPPs were replaced at the same location with a NGCC that will generate the same amount of electricity as the CPPs. The water diversion (WR_{CPPs}) for this demand site (about 47.5 Mm^3/year) was decreased to an estimated water demand ($WR_{NGCC} = WD_{NGCC}$) needed by a NGCC, from which a closed-loop cooling system was assumed. Two alternatives of water demands of the NGCC (low and high water demand) were used to capture the uncertainty of different options of NGCC that could replace the CPPs. The water savings were left on Falcon Dam to be used for the rest of the demand sites. Equation 4.2 was used to determine the new water demand:

$$WR_{NGCC} = WD_{NGCC} = \left(\frac{W_{witdrawal}}{GWh_{generated}}\right)_{inNGCC} \left(\frac{GWh_{fromCPPs}}{year}\right) \tag{4.2}$$

where $\left(\frac{W_{witdrawal}}{GWh_{generated}}\right)_{inNGCC}$ is the water withdrawal per GWh generated by a NGCC estimated in the water demand calculator by conducting a statistical analysis of NGCC power plant in Texas [94, 95]. The upper and lower boundaries of the 95% confidence interval from the analysis (0.25 and 0.32 gal/kWh) was used as low and a high water demand alternative, which range covers the average values found in previous analysis of Texas' NGCCs (0.26 [96] and 0.25 [54] gal/kwh). The $\left(\frac{GWh_{fromCPPs}}{year}\right)$ is the electricity generated by the CPPs (16,388 GWh/year [87]). The return flow of the NGCC (RF_{NGCC}) was estimated for a low and high water withdrawal and demand alternatives using Equation 4.3:

$$RF_{NGCC} = 1 - \frac{\left(\frac{W_{consumed}}{GWh_{generated}}\right)_{forNGCC}}{\left(\frac{W_{withdrawal}}{GWh_{generated}}\right)_{forNGCC}} \tag{4.3}$$

where $\left(\frac{W_{consumed}}{GWh_{generated}}\right)_{forNGCC}$ is the water consumption of the NGCC in Texas, which was assumed the similar as the average water consumption of similar power plants in Texas [96].

Scenario 2

As in Scenario 1, the CPPs were replaced with an equivalent NGCC at the same geographic location, but the water savings (Water Savings = Water Right - Water Delivered) were sold to one of the irrigation districts located in the Mexican side of the border downstream from Amistad Dam, showed in Figure 4.4 (DR050, DR026 and DR025). This scenario is divided into 3 sub-scenarios, one for each case of selling the water savings to each of the irrigation districts.

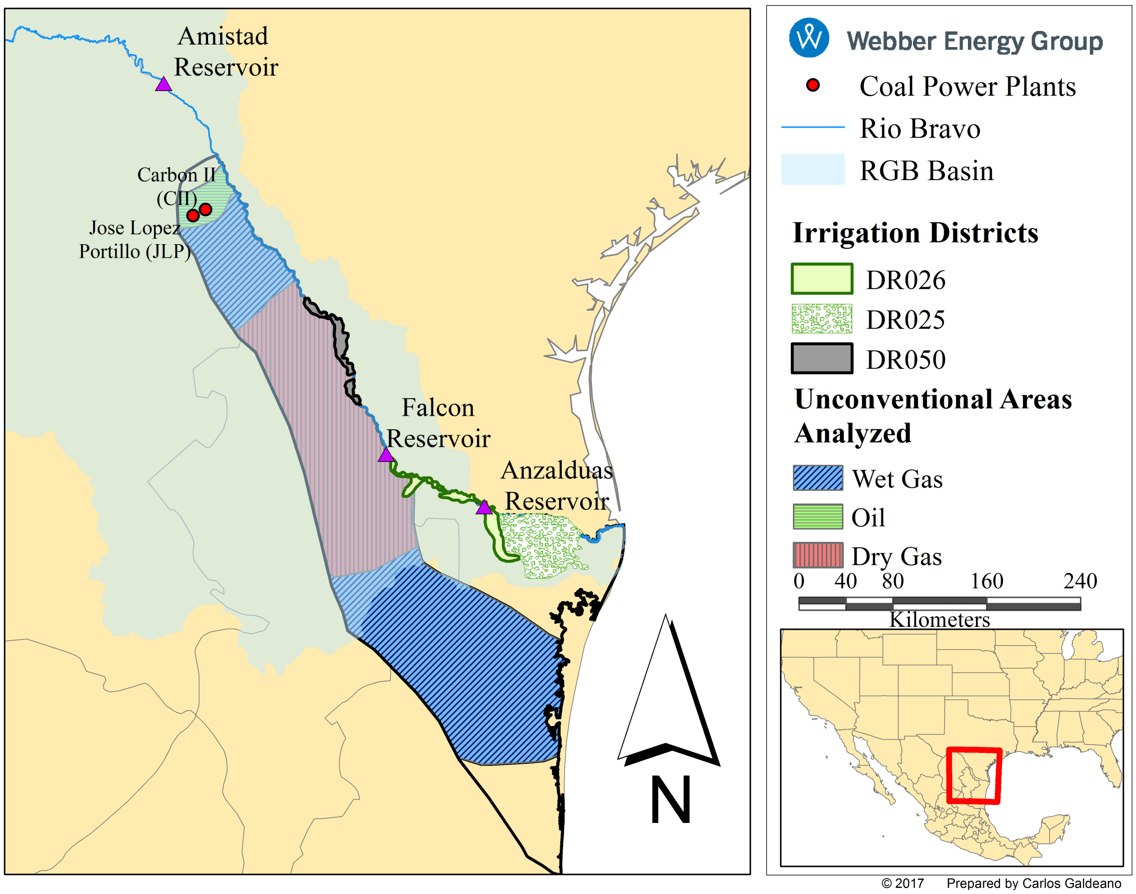

Figure 4.4: Water made available by switching the CPPS for a NGCC could be used in downstream irrigation districts shown as a) DR050 ($WR_{DR050} = 30Mm^3/year$), b) DR026 ($WR_{DR026} = 464Mm^3/year$), and C) DR025 ($WR_{DR025} = 860Mm^3/year$).

Conveyance losses due to the losses from transport of the water savings to the irrigation districts were estimated. Equations 4.4—4.6 were used to estimate the conveyance losses (CL) for each irrigation district:

$$CL_{DR050} = CL_{Amistad\,to\,DR050} \tag{4.4}$$

$$CL_{DR026} = CL_{Amistad\,to\,Falcon} \tag{4.5}$$

$$CL_{DR025} = 1 - \left(1 - CL_{Amistad\,to\,Falcon}\right)\left(1 - CL_{Falcon\,to\,DR025}\right) \tag{4.6}$$

where CL_{DR050} is the conveyance loss from the Amistad dam to the withdrawal node of the irrigation district DR050 (estimated with the validated RGB WEAP model). The CL_{DR026} is the conveyance loss for irrigation district DR026 that is equal to the conveyance loss from Amistad dam to Falcon dam (estimated with the validated RGB WEAP model). The CL_{DR025} is the conveyance loss for irrigation district DR025 and depends on the conveyance loss from Amistad to Falcon dam ($CL_{Amistad\,to\,Falcon}$) and from Falcon dam to its withdrawal node ($CL_{Falcon\,to\,DR025}$).

Scenario 3

In this scenario, the CPPs were replaced with an equivalent NGCC in the same geographic location, and the water savings (Water Savings = Water Right - Water Delivered) was sold to HF sites in the nearby region of the power plant on the Mexican side. The increase in domestic annual water demand in the region ($AWD_{migrationHF}$) caused by increase in population due to the jobs generated from the HF wells supplied with the water savings ($HFwells_{savings}$) was estimated using Equation 4.7:

$$AWD_{migration\,HF} = WD_{capita}\left[\frac{jobs}{HF\ well}\frac{Pop}{Job}_{Coah}\right]\left(HF\ wells_{savings}\right) \tag{4.7}$$

where WD_{capita} is the average water consumption per capita per year in Mexico (102 m^3/year per capita [98]). The $\frac{jobs}{HF\ well}$ is the number of jobs that could be created per HF well, which was assumed to be similar to the estimated in Texas' EFS (between 9 and 13 jobs/well [97]). The $\frac{Pop}{Job}_{Coah}$ is the total population per jobs of Coahuila (the state overlaying the CPPs), which is around 2.3 people per job [99].

4.2.3 Economic Analysis

An economic analysis was conducted in each scenario in which the water was sold to other user (Scenario 2 and 3). The economic analysis consisted on estimating the breakeven prices at which the sales of the water savings plus the economic benefits from shifting the CPPs for a NGCC would offset the costs implied on this shift. To determine these water prices, the present value of the costs and benefits from shifting the power plant technology was set to zero (PV_{shift}).

The water prices were estimated assuming (1) a period (n) of 20 years starting this year, (2) a discount rate (i) of 7.84% that was the offered by CFE bonds [100], (3) an exchange rate of 18.90 MXP per USD (2017 average [101]), (4) a total electricity generation (tot_{elect}) of 16,388 GWh/year based on the 2016 generation from the CPPs [87], (5) an installed capacity of 2,600 MW, and (6) the fuel prices estimated in SENER's forecast [102]. Equation 4.8 was used to determine the price of the water savings at which PV_{shift} would be equal to zero:

$$PV_{shift} = PV_{cost} - PV_{benefits} = 0 \tag{4.8}$$

where PV_{cost} and $PV_{benefits}$ are the present values of the costs and benefits, implied from shifting the CPPs for a NGCC. The costs include (a) the investment cost to build the NGCC (CI_{NGCC}), (b) the differential of the operation and maintenance (ΔOM), and (c) the differential of the fuel costs for the different technologies ($\Delta Fuel$). To capture the uncertainty of the fuel cost forecast, two alternatives of the present value were estimated based on extreme values of coal (Co) and natural gas (NG) costs (low NG-high Co costs, and high NG-low Co costs). Equation 4.9 was used to estimate PV_{cost} with both fuel costs alternatives:

$$PV_{cost} = CI_{NGCC} + \sum_{n=1}^{20} \frac{\Delta OM + \Delta Fuel}{(1+i)^n} \tag{4.9}$$

where CI_{NGCC} was estimated assuming a total installed capacity required of 2,600 MW and a unitary cost of 970,000 USD/MW (2013 EIA data [103] updated with U.S. inflation). The ΔOM was estimated assuming that the CPPs and proposed NGCC would have a similar average unitary cost as the power plants in Texas (around 5 USD/MWh and 3 USD/MWh, respectively [104]). The $\Delta Fuel$ in both alternatives were estimated using SENER's forecast of NG and Co costs in Mexico [102].

The economic benefits ($PV_{benefits}$) in Equation 4.8 include (a) the savings from the refurbishment required to extend the lifetime of the CPPs (LE_{JLP} and LE_{CII}), (b) the savings from the decommission of the CPPs in year 20 (D_{CPPs}), (c) the benefits from selling the assets of the NGCC at the end of year 20 (T_{assets}), and (d) the benefits from selling the water savings ($Water_{user_x}$, where x refers to an irrigation district in Scenario 2 or a HF user in Scenario 3). Equation 4.10 was used to estimate these economic benefits:

$$PV_{benefits} = \frac{LE_{JLP}}{(1+i)^5} + \frac{LE_{CII}}{(1+i)^{16}} + \frac{D_{CPPs}}{(1+i)^{20}} + T_{assets} + WB_{user_x} \tag{4.10}$$

where $\frac{LE_{JLP}}{(1+i)^5}$ and $\frac{LE_{CII}}{(1+i)^{16}}$ are the present values of the investment required to extend the lifetime of the CPPs in years 5 and 16 respectively, which was estimated using a unitary price of 0.322 million USD per MW (1990 EPA data [105] updated with U.S. inflation). The D_{CPPs} was assumed to be similar to costs for decommissioning a plant in the United States (2004 data updated with US inflation [106]), and T_{assets} was estimated the two alternatives of extreme values of the fuel costs (low NG-high Co costs, and high NG-low Co costs) using Equation 4.11:

$$T_{assets} = \sum_{n=21}^{40} \frac{(R_{elect} - (Fuel + OM))\,(1 - \tau)}{(1+i)^n} \tag{4.11}$$

where the useful life of the NGCC was assumed to be of 40 years, R_{elect} is the future revenues from the electricity that the power plant could sell from year 21 to 40, and the income tax (τ) was discounted after the costs were subtracted from the revenues. The future revenues (R_{elect}) were estimated with the average locational marginal price (0.03 USD/kWh) of the closest node to the power plants, which was estimated by SENER [107].

The benefits from selling the water savings (WB_{user_x}) in Scenarios 2 and 3 includes (a) the potential annual volume of water savings from shifting the CPPs for a NGCC and sold to user x (Vol_{saved_x}), which would vary depending on the scenario analyzed, and (b) the price of the water savings (WP) required to make the PV_{shift} equal to zero. Equation 4.12 was used to determine the benefits from selling the water savings:

$$WB_{user_x} = \sum_{n=1}^{20} \frac{Vol_{saved_x} WP}{(1+i)^n} \tag{4.12}$$

where Vol_{saved_x} was estimated in each period (n) by bootstrapping from the potential annual water savings allocated to user x in each scenario analyzed in a given year in the 60 year period simulated in the RGB WEAP model. In Scenario 3 the annual water demand increased by people moving to the region due to the jobs generated from the HF wells supplied with the water savings was subtracted from the water allocated for HF (Equation 4.7). The water price (WP) was found by setting the present value (PV_{shift}) of the costs minus benefits from shifting the power plant technology equal to zero. Finally, 1,000 iterations of the economic model to find the water price of the water savings was run to capture the uncertainty of the annual water savings that could happen in a given year.

4.3 Findings and Discussion

4.3.1 Water Availability

The widely used performance parameters criteria of reliability, resilience, and vulnerability [108, 109] were estimated to evaluate how the different strategies affect the water supply of different users in the region (irrigation districts, and power plants). The reliability represents the frequency at which the monthly demand is satisfied (as percentage). The resiliency shows the probability the system recovers from a deficit period (as percentage), and the vulnerability refers to the average magnitude of deficits (as Mm^3/month). Equations 4.13—4.15 were used to determine these performance parameters:

$$Reliability = \frac{\#\, of\, times\, D_t = 0}{\#\, simulation\, periods} \tag{4.13}$$

$$Resilience = \frac{\#\, of\, times\, D_t = 0\, follows\, D_t > 0}{\#\, oftimes\, D_t > 0\, occured} \tag{4.14}$$

$$Vulnerability = \sum_{D_t > 0} \frac{D_t}{\#\, of\, times\, D_t > 0\, occured} \tag{4.15}$$

where D_t is the water deficit at each period simulated and was estimated with Equation 4.16.

$$D_t = \begin{cases} X_T - X_t & \rightarrow if\, X_T > X_t \\ 0 & \rightarrow if\, X_T = X_t \end{cases} \tag{4.16}$$

where X_t is the amount of water delivered (m^3), and X_T is the amount of water demand (m^3).

The performance criteria estimated for the power plant and irrigation districts (DR050, DR026, DR025) are shown in Table 4.1. These results are presented as the change in each performance parameter with respect with the Baseline Scenario. Two alternatives were analyzed using a low and high water required for the NGCC. The performance parameters that improved are in green italic and the ones that decreased are red underlined. For instance, the reliability or frequency with which the water demand of the power plant is satisfied was increased between 17%—18% in Scenario 1 and between 20%—23% for Scenarios 2 and 3.

The results presented in Table 4.1 show that the water delivered to the power plant increased in all the scenarios analyzed. For the rest of the users analyzed, the performance parameters indicate that the water delivered also increased with respect to the current conditions. In some cases, the vulnerability parameter for some users is worse than in the Baseline Scenario. The increase of the vulnerability is because there are fewer times in which the water demands of the users are not satisfied making the average magnitude of the deficit bigger.

Table 4.1: Change of the performance criteria of the water delivered to the power plant and irrigation districts (DR050, DR026, DR025) in Scenarios 1, 2 and 3 with respect to the Baseline scenario. In italic are the cases where the parameters improved and the parameters that decreased are underlined.

	User	Scenario 1	Scenario 2	Scenario 3
Reliability Δ Baseline (%)	Power Plant	*17—18%*	*20—23%*	*20—23%*
	DR050	*17—18%*	*18—19%*	0%
	DR026	*8—12%*	*11—12.5%*	0%
	DR025	*17—18%*	0%	0%
Resilience Δ Baseline (%)	Power Plant	*0—1%*	0%	0%
	DR050	*0—1%*	*0—1%*	0%
	DR026	0%	*1—1.3%*	0%
	DR025	*0—1%*	0%	0%
Vulnerability Δ Baseline (Mm^3 per month)	Power Plant	*(1)—(1.3)*	*(1.2)—(1.5)*	*(1.2)—(1.5)*
	DR050	<u>0.2—0</u>	<u>0.63—0.61</u>	0
	DR026	*(1)—(1.1)*	<u>2.3—2.2</u>	0
	DR025	<u>5.7—1.8</u>	*(0.3)—(0.4)*	0

To better understand the increase in water delivered to the irrigation districts Scenario 2, an analysis of the extra revenue that could be generated with this water was conducted. Table 4.2 shows a range of percentage increase in the annual average extra revenue for each irrigation district in the sub-scenarios in Scenario 2. This range was estimated using the results from the WEAP model that considered the two alternatives of water withdrawals (High WW and Low WW) that a NGCC could require. The average and boundaries (upper and lower) of the 95% confidence interval was estimated from bootstrapping the potential annual water savings that could be allocated to each irrigation district from the results of the 60 year simulation of the RGB WEAP model. This bootstrapping was conducted through 1,000 iterations to capture the uncertainty of the potential extra annual water allocated to the irrigation districts that could happen in a given year.

As Table 4.2 displays, the irrigation district that is able to increase its production most is DR050, followed by DR026 and DR025. The main reason is because DR050 has the smallest water right of the three districts. In addition, DR050 is the closest irrigation district to the power plant, thus, less water is lost due to seepage. The median annual revenues per unit of water and median annual revenues were obtained from Conagua's agricultural statistics reports from 1997 to 2013 [110–125]. The exchange rate considered was 18.90 MXP per USD [101].

Table 4.2: Average annual extra revenues with the water savings sold to the irrigation districts (DR050, DR026, DR025) in each sub-scenario in Scenario 2.

Irrigation Districts	Median Annual Revenue per unit of water (USD/m^3)	Median Annual Revenue (Million USD/year)	Annual Extra Revenue(%)		
			Lower Bound with High WW	Average (High-Low WW)	Upper Bound with Low WW
DR050	\$ 0.28	\$ 2.4	222 %	235—294%	309 %
DR026	\$ 0.08	\$ 36.8	4 %	4.2—5.1%	5.4 %
DR025	\$ 0.12	\$ 80.7	2 %	2.2—2.7%	3 %

The annual water savings that could be allocated for HF users in Scenario 3 were analyzed by estimating a range of annual wells that could be supplied and the energy that could be extracted in a 20-year period from these wells. The range of these potential annual HF wells was estimated considering (a) the two alternatives of water withdrawals (High WW and Low WW) that a NGCC would require, (b) the upper and lower boundaries from the 95% confidence intervals estimated in each of these alternatives, and (c) an average water withdrawal required per well of 8.77 Mgal/well, which was estimated with Texas' EFS data from FracFocus database [5]. The 95% confidence interval was estimated from bootstrapping from the results of the 60 year simulation of the RGB WEAP model the potential annual water savings that could be allocated for HF. This bootstrapping was conducted through 1,000 iterations to capture the uncertainty of the potential annual water savings that could happen in a given year. Also the annual water demand increased by people moving to the region due to the jobs generated from the HF wells supplied with the water savings was subtracted from the results.

Figure 4.5 shows the estimated range of the annual HF wells that could be supplied (482—669 wells/year) with the water savings in Scenario 3 compared with the number of wells drilled between 2009 and 2016 in Texas' EFS. The number of wells drilled in Texas' EFS have were normalized by the amount of water required per HF well in each year compared with 2016 due to changes in water required per HF well, which relates to advances of the HF process throughout time (e.g. longer laterals, different proppants, or different additives).

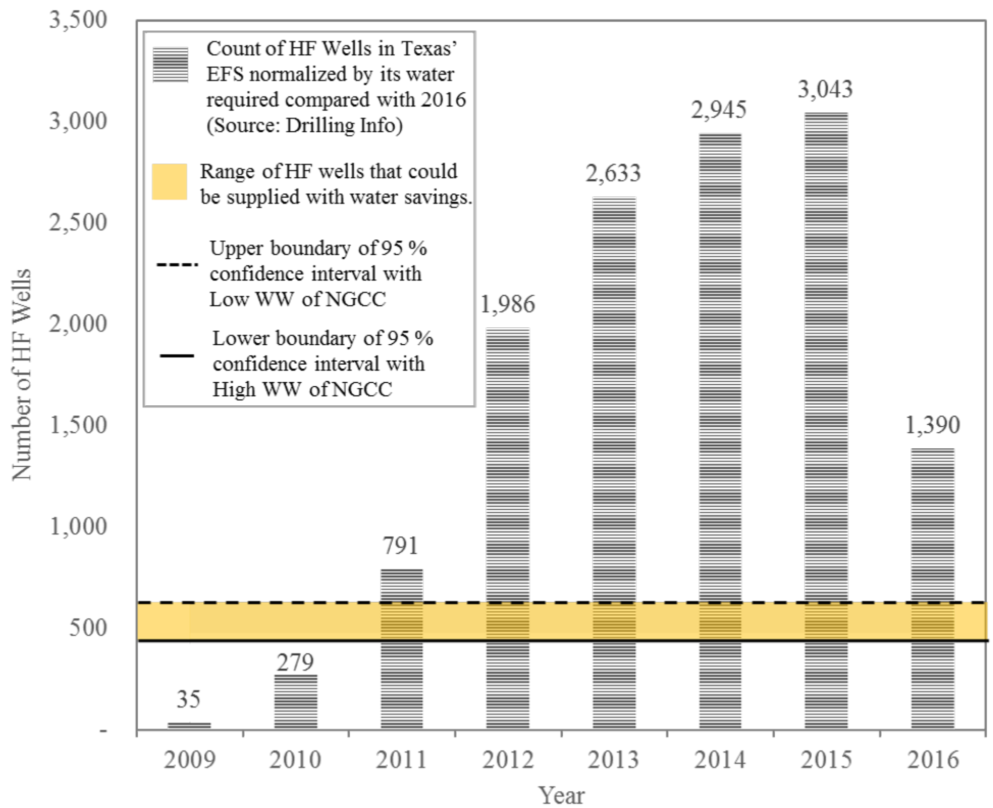

Figure 4.5: The annual HF wells that could be supplied with the water savings in Scenario 3 range from 482 to 669 wells/year assuming the upper and lower boundary of the low and high water withdrawal of the NGCC alternatives, respectively.

Figure 4.6 shows an annual and cumulative range of the energy that could be extracted in a 20-year period from HF wells that could be supplied with the water saving in Scenario 3. This annual and cumulative energy was estimated using the average oil and gas production in a 20-year period from 2014—2017 HF wells in Texas' EFS across the Mexican border, which was obtained from the Drilling Info database [50]. This potential cumulative energy to be extracted in 20 years with the HF wells supplied with one year of water savings ranged from 0.78 to 1.02 Quads. Most of this energy could extracted during the first year, ranging from 0.28 to 0.37 Quads, which represents about 5% of Mexico's annual energy consumption assuming its current annual consumption of 7.5 Quads [73, 74].

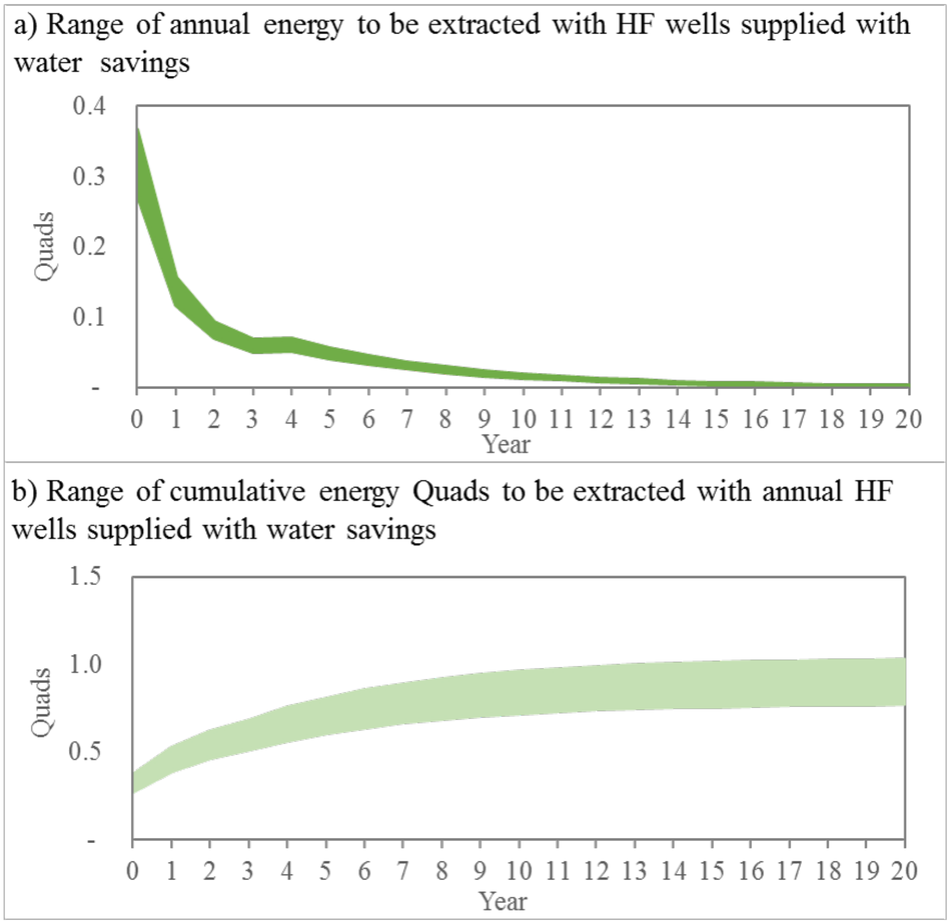

Figure 4.6: The cumulative energy that could be extracted from the annual HF wells supplied with the water savings in Scenario 3 range between 0.78 and 1.02 Quads, from which around 35% could be extracted in the first year.

4.3.2 Economic Analysis

Figure 4.7 shows the breakeven prices at which the sales of the water savings plus the economic benefits from shifting the CPPs for a NGCC would offset the costs implied on this shift. These water prices were analyzed for two different extreme coal and natural gas cost combinations (low NG-high Co costs, and high NG-low Co costs). The range shown for each alternative include the upper and lower boundaries from the 95% confidence intervals estimated with Low and High WW of the NGCC. The 95% confidence interval was estimated from bootstrapping from the results of the 60 year simulation of the RGB WEAP model the potential annual water savings for irrigation districts or HF users in Scenarios 2 and 3, respectively.

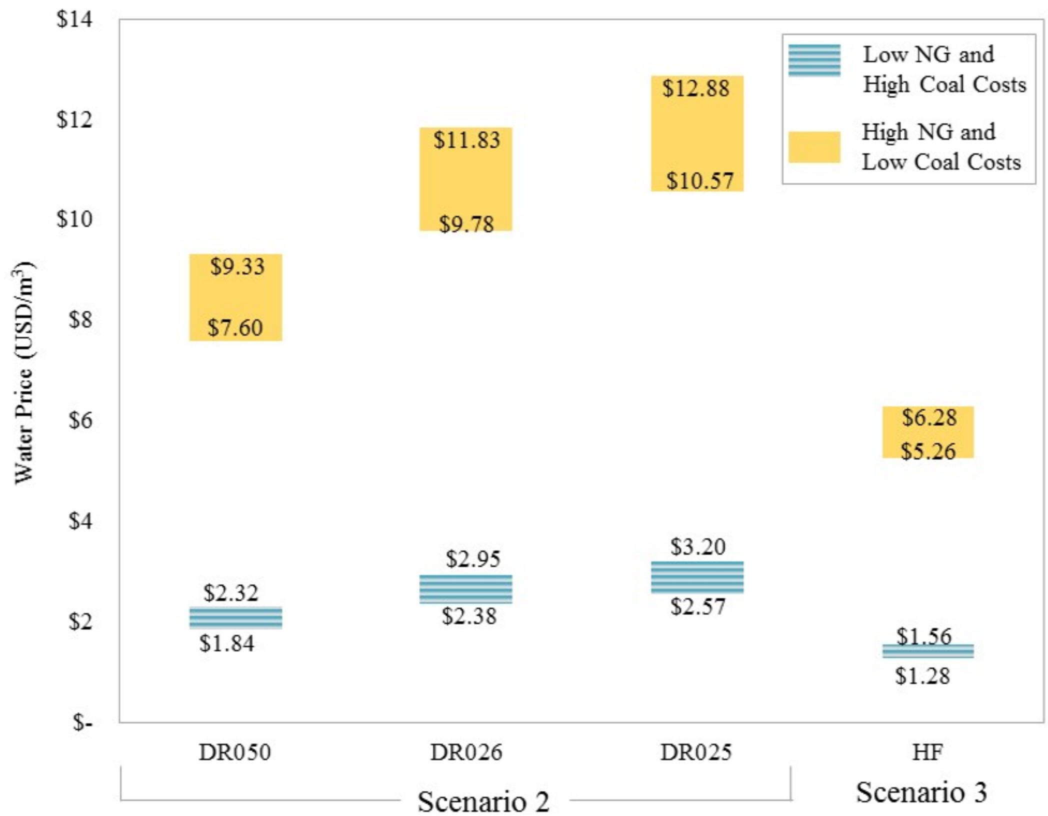

Figure 4.7: The water prices required to offset the cost of the shift from the CPPs to the NGCC seem too high for the irrigation district, but reasonable for the potential HF users.[NG = natural gas]

The price of water reported by a Mexican irrigation district in the RGB (DR005 Delicias) upstream from the irrigation districts analyzed ranges between \$0.013—\$0.02 USD/m^3 [126], which is similar to the price paid by irrigation districts in the Texas' side of the region (\$0.01 usd/m^3 [1]). Furthermore, the median revenues from the crops harvested per unit of water in the irrigation districts analyzed ranged between \$0.08 and \$0.28 USD/m^3 from 1997-2013 [110–125], while the average water price for HF users in the EFS in Texas was on average \$3.9 USD/m^3 due to the higher revenue per unit of water that this activity could generate [1]. Therefore, HF sites could be the users most likely to pay for the water savings derived from shifting the CPPs for a NGCC.

4.4 Conclusion

Mexico's energy reform is expected to intensify activities in the energy sector which might yield additional natural gas that could be used for electricity generation, displacing existing coal-fired power plants. Doing so would have a significant impact on the water sector. This study quantifies water availability effects of Mexico's energy reform in northern Mexico using the RGB transboundary basin as a case study. The following four potential scenarios derived from the energy reform were analyzed:

1. Baseline Scenario: Normal water allocation over years 1940 to 2000.

2. Scenario 1: Two Mexican coal-fired power plants (CPPs) were substituted with a natural gas combined cycle (NGCC) that would generate the same amount of electricity as the original CPPs. The water savings for changing the CPPs to NGCC (assuming closed-loop cooling system) are left in Falcon dam for the rest of the users reallocation.

3. Scenario 2: Changes made in Scenario 1, but the water savings were sold to one of the irrigation districts (DR050, DR026 and DR025) located in the Mexican side of the border downstream from Amistad Dam.

4. Scenario 3: Changes made in Scenario 1, but the water savings were sold to HF sites in the nearby area.

The results suggest that switching the existing power production facilities in Mexico from traditional coal-fired steam cycle to natural gas combined cycle would increase water availability for current (e.g. irrigation districts) and new users (e.g. HF companies); however, this available volume is small compared to the overall RGB basin's water demand. In Scenario 2, on average the water savings could increase 222—309%, 4—5.4%, and 2—3% the revenues of irrigation districts DR050, DR026, and DR025 respectively. The irrigation district closer to the power plant (DR050) could be more interested in buying the water savings from the power plant due to (1) its small water right in comparison with the other two irrigation districts (DR025 and DR026), (2) its proximity to the power plant resulting in lower conveyance losses, and (3) the 222—309% potential increase in its average revenue per year. Nonetheless, according to the economic analysis conducted, the water prices required to offset the costs in Scenario 2 would range from \$1.84—\$12.88 USD/m^3, which is higher to what irrigation districts usually pay for water in the region (\$0.013—\$0.02 USD/m^3 [126]) and higher than the median revenues from the crops harvested per unit of water in the irrigation districts analyzed (\$0.08 - \$0.28 USD/m^3 [110–125]).

In Scenario 3, the annual HF wells that could be supplied with the water savings would range between 482 to 669 wells/year assuming the upper and lower boundary from the 95% confidence interval of a low and high water withdrawal required for the NGCC, respectively. These HF wells could extracted between 0.78 to 1.02 Quads in their 20-year lifetime, from which around 35% could be extracted in the first year. According to the economic analysis, the water prices required to offset the cost in this scenario would range from \$1.28—\$6.28 USD/m^3, which is similar to the price that HF users have paid in the Texas' EFS (on average 3.9 USD/m^3 [1]). Future work should be conducted to analyze other benefits for shifting the CPPs to a NGCC besides increasing the water availability in the RGB and the water prices required to offset this shift, such as the benefits from reducing carbon emissions from the electricity generation process. Also, future work could consider analyzing a water market in which the water prices would be determined by the value that each type of user could derive from the water used as input in their activities. Furthermore, future research should include analysis of the impacts of changes in weather patterns derived from climate change to the scenarios analyzed, which could include more frequent and more intense wet and dry periods.

Chapter 5

Evaluating increase in water availability for current and potential new users from shifting the irrigation technology and practices from two Mexican irrigation districts in the middle Rio Grande/Bravo

5.1 Introduction

In the middle RGB region, according to SENER's 5-year plan [10], three shale areas are projected to be explored and developed through HF. As Figure 5.1 shows, two irrigation districts overlay these areas (DR050 and DR006), which have a water right of 28.82 and 27.71 Mm^3, respectively. The irrigation technology employed by these irrigation districts is furrow irrigation [127]. The water rights combined of these irrigation districts account for 1% of the total water rights allocated for irrigation in the Mexican side of the RGB [89].

In 2004, three irrigation districts (DR005, DR090, DR103) on the Mexican side of the border submitted a "Minute" to the IWBC to inform their intention to conduct improvements in their irrigation practices and technology to increase their efficiency [8, 58]. Among these improvements included lining of canals, installing of measurement structures to improve the operations of the distribution networks, leveling the land, rehabilitating of pumping equipment, installing drip irrigation and sprinkling systems, and rehabilitating lines tubing and irrigation with multi-gated piping [8].

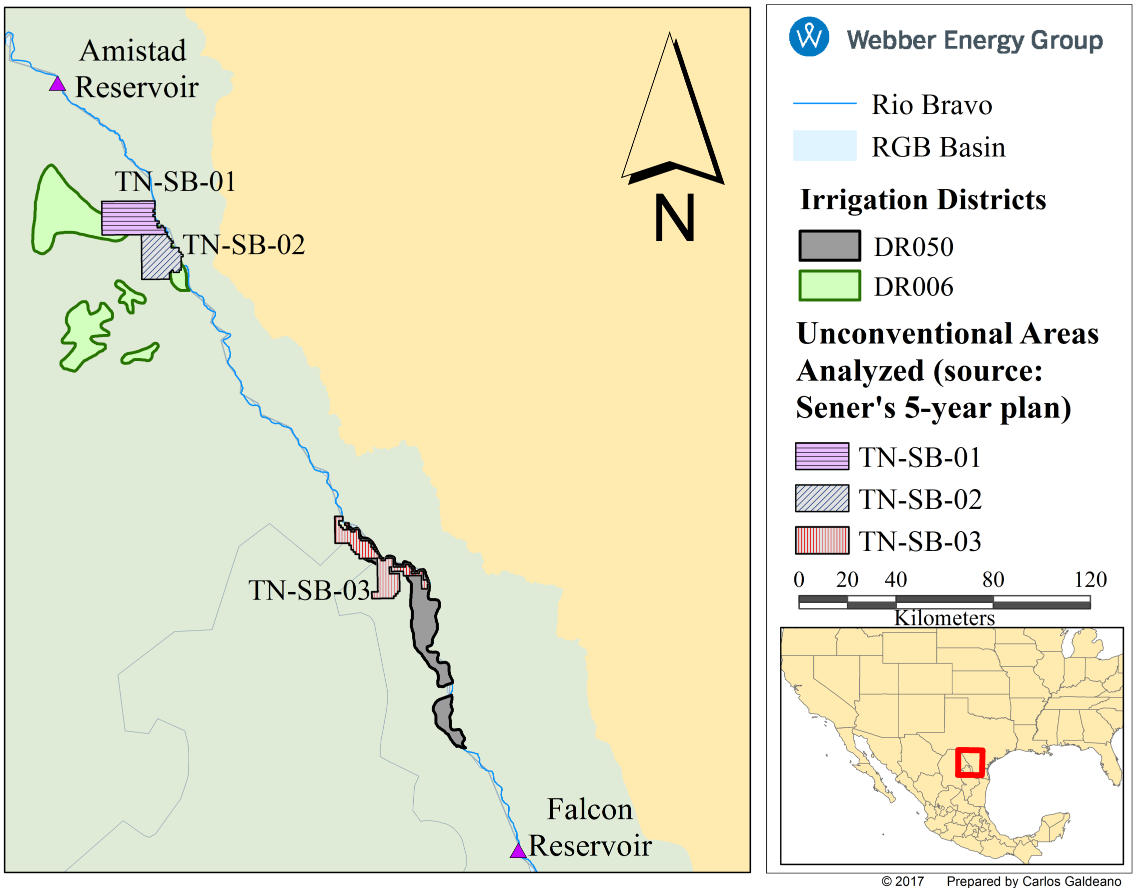

Figure 5.1: Two irrigation districts (DR050 and DR006) that have water rights from the RGB overlay 3 shale areas expected to be explored and developed according to SENER's 5-year plan.

The main contribution of this chapter is to develop a methodology to assess the potential changes in water availability in a water stress basin due to a shift of current irrigation technologies to more water efficient practices. This study considers the transboundary RGB basin as a case study due to (1) the geographic location of 3 prospective shale areas to be developed according to SENER's 5-year plan, (2) the existing water stress due to over allocated water rights in the RGB basin, and (3) the presence of two Mexican irrigation districts overlaying these shale areas. It is hypothesized that changing the current irrigation practices, similarly to what three irrigation districts in the region conducted in 2004, will generate water savings and thus an increase in water available to add new users such as HF users.

5.2 Methodology

The methodology employed to assess the potential changes in water availability in the RGB due to a shift of irrigation practices in the two irrigation districts analyzed is shown in Figure 5.2. The WEAP water allocation model of the RGB basin [89], was coupled with an irrigation water demand calculator that takes into account changes on water demand due to a shift in irrigation technologies and practices of the two irrigation districts overlaying the shale areas analyzed. The savings in the water demand of the irrigation districts was assumed to be similar to the savings that previous irrigation districts achieved after conducting improvements in their technology and practices. The following potential scenarios were analyzed after coupling the two models:

1. Baseline Scenario: Normal water allocation over years 1940 to 2000.
2. Scenario 1: The two irrigation districts analyzed improved their irrigation technology and practices to maintain their crop yield while saving water. These improvements were assumed to be similar to the ones made by Irrigation District DR005 in 2004 [8] The water savings were allocated to HF sites in the shale areas expected to be explored and developed according to SENER's 5-year plan.
3. Scenario 2: Similar to Scenario 1, but it was assumed that the irrigation technologies and practices improvements were similar to the ones made by Irrigation District DR090 in 2004 [8].

4. Scenario 3: Similar to Scenario 1, but it was assumed that the irrigation technologies and practices improvements were similar to the ones made by Irrigation District DR103 in 2004 [8].

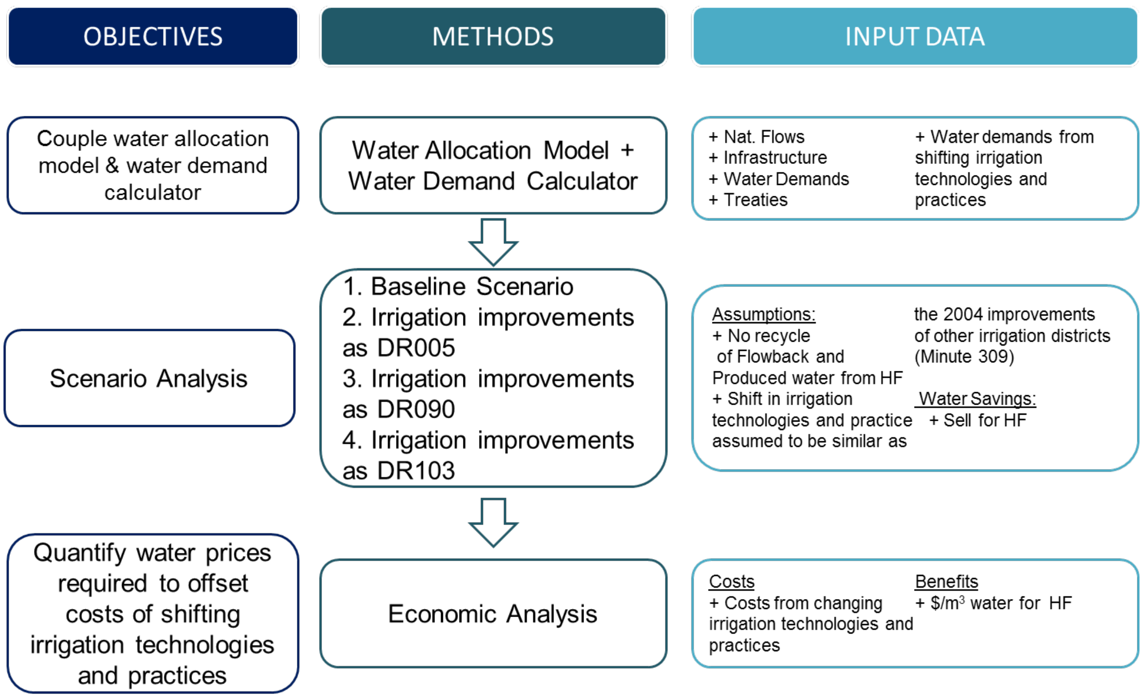

Figure 5.2: Four scenarios were analyzed after coupling a water allocation model with an irrigation water demand calculator that considers the water savings from shifting of the irrigation technology and practices of the two irrigation districts overlaying the shale areas analyzed.

The reliability, resilience, and vulnerability parameters of the water supplied to the irrigation districts was estimated in each scenario. In addition, the potential annual number of wells that could be supplied for HF and the total energy that could be extracted throughout the lifetime of these wells was estimated in Scenarios 1, 2, and 3. Finally, an economic analysis was conducted to identify the breakeven prices at which the sales of the water savings would offset the costs from shifting the irrigation technology and practices in the two irrigation districts analyzed.

5.2.1 Water Allocation Model and Irrigation Water Demand Calculator

The RGB WEAP allocation model, described in Chapter 4, was coupled with an irrigation water demand calculator that modified the water demand of the irrigation districts DR050 and DR006. The new water demands were estimated assuming these irrigation districts would conduct the same improvements that DR005, DR090, and DR103 conducted in 2004 [8]. These improvements included:

- lining of canals (main and smaller branch) to reduce losses. Also, improving control systems and installing measurement structures to improve the operation of the distribution networks,
- installing low pressure supply systems for the water distribution,
- leveling the land, rehabilitating of pumping equipment, installing drip irrigation and sprinkling systems, and
- rehabilitating lines tubing and irrigation with multi-gated piping.

The improvements conducted by these irrigation district in 2004 were able to increase their efficiency significantly. Table 5.1 shows the water savings achieved by each irrigation district in 2004 after conducting these improvements. The global efficiency of these irrigation districts is defined as the ratio of the water consumed with respect to the water withdrawal and includes the conveyance and application efficiencies [8,58]. The water savings achieved from the improvements were 40%, 26%, and 30% for the DR005, DR090, and DR103, respectively.

Table 5.1: Water savings of the 3 irrigation districts that improved their practices and technology in 2004 [8].

Irrigation District	Base Volume (Mm^3)	Base Global Efficiency (%)	Global efficiency after improvements (%)	Savings after improvements (Mm^3)	Savings after improvements (%)
DR005	857	33%	55%	343	40%
DR090	96	35%	47%	25	26%
DR103	91	33%	48%	28	30%

5.2.2 Scenario Analysis

The results from the irrigation water demand calculator were used to modify the WEAP model to simulate the four scenarios described below.

Baseline

This scenario establishes the baseline by running the WEAP model with historic conditions. The water right of the Irrigation Districts DR050 and DR006 (WR_{DR050} and WR_{DR006}) was equal to their water demand (WD_{DR050} and WD_{DR006}).

Scenario 1

In this scenario, it was assumed that the potential water savings from the improvements in technology and practices of DR050 and DR006 would be similar to the ones achieved by DR005 according to Minute 309. The water diversion (WR_{DR050} and WR_{DR006}) for these demand sites (about 28.82 and 27.71 Mm^3/year, respectively) was maintained, but the water demands ($WD_{DR050_{S1}}$ and $WD_{DR006_{S1}}$) was adjusted based on the water savings achieved by the improvements conducted by DR005 in 2004. Once the new water demand was met, it was assumed that water savings would be sold to the HF sites in the nearby prospective shale areas. Equations 5.1—5.2 were used to estimate the new water demands for DR050 and DR006:

$$WD_{DR050_{S1}} = WR_{DR050}\left(1 - S_{DR005}\right) \tag{5.1}$$

$$WD_{DR006_{S1}} = WR_{DR006}\left(1 - S_{DR005}\right) \tag{5.2}$$

where S_{DR005} is the water savings achieved by the DR005 after the improvements conducted in 2004 (around 40% of water right).

Scenario 2

In this scenario, it was assumed that the potential water savings from the improvements in technology and practices of DR050 and DR006 would be similar to the ones achieved by DR090 according to Minute 309. The water diversion for these demand sites was maintained, but in this scenario the water demand ($WD_{DR050_{S2}}$ and $WD_{DR006_{S2}}$) was adjusted based on the water savings achieved by the improvements conducted by DR090 in 2004. Similar to Scenario 1, once the new water demand was met, it was assumed that water savings would be sold to the hydraulic fracturing sites in the nearby prospective shale areas. Equations 5.3—5.4 were used to estimate the new water demands for DR050 and DR006:

$$WD_{DR050_{S2}} = WR_{DR050}\left(1 - S_{DR090}\right) \tag{5.3}$$

$$WD_{DR006_{S2}} = WR_{DR006}\left(1 - S_{DR090}\right) \tag{5.4}$$

where S_{DR090} is the water savings achieved by the DR090 after the improvements conducted in 2004 (around 26% of water right).

Scenario 3

In this scenario, it was assumed that the potential water savings from the improvements in technology and practices of DR050 and DR006 would be similar to the ones achieved by DR103, according to Minute 309. The water diversion for these demand sites was maintained, but in this scenario the water demand ($WD_{DR050_{S3}}$ and $WD_{DR006_{S3}}$) was adjusted based on the water savings achieved by the improvements conducted by DR103 in 2004. Similar to Scenario 1, once the new water demand was met, it was assumed that water savings would be sold to the HF sites in the nearby prospective shale areas. Equations 5.5—5.6 were used to estimate the new water demands for DR050 and DR006:

$$WD_{DR050_{S3}} = WR_{DR050}\,(1 - S_{DR103}) \tag{5.5}$$

$$WD_{DR006_{S3}} = WR_{DR006}\,(1 - S_{DR103}) \tag{5.6}$$

where S_{DR103} is the water savings achieved by the DR103 after the improvements conducted in 2004 (around 30% of water right).

5.2.3 Economic Analysis

An economic analysis was conducted in scenarios 1, 2, and 3. The economic analysis consisted on estimating the breakeven prices at which the sales of the water savings would offset the costs implied on the irrigation technology and practices improvements. To determine these water prices, the present value of the costs and benefits from conducting such improvements was set to zero ($PV_{improvement}$). The water prices were estimated assuming (1) a period (n) of 10 years starting this year, (2) three alternatives of discount rate (i) of 6,7 and 8%, (3) an exchange rate of 18.90

MXP per USD [101], and (4) a cost per unit of water saved assumed to be similar to what DR005, DR090 and DR103 invested on their improvements in 2004 updated to 2016 values with annual consumer price index [128] (Table 5.2).

Table 5.2: The cost per unit of water saved from 2004 was updated to estimate the total cost of the improvements proposed for the irrigation districts analyzed in each scenario.

Irrigation District	Improvements Costs (Million MXP 2004)	Annual Water Savings (Mm^3/year)	Cost per unit water saved (MXP/m^3 2004)	Cost per unit water saved (USD/m^3 2016)
DR005	$ 1,359	343	$ 3.9	$ 0.35
DR090	$ 110	25	$ 4.4	$ 0.39
DR103	$ 65	28	$ 2.3	$ 0.20

Equation 5.7 was used to determine the price of the water savings at which the present value ($PV_{DRt_{Si}}$) of the economic analysis for the irrigation districts analyzed DR050 and DR006 (DRt) in each scenario (Si) would be equal to zero:

$$PV_{DRt_{Si}} = PV_{cost\ DRt_{Si}} - PV_{benefits\ DRt_{Si}} = 0 \tag{5.7}$$

where $PV_{cost\ DRt_{Si}}$ and $PV_{benefits\ DRt_{Si}}$ are the present values of the costs and benefits from implementing the improvements in the irrigation districts DRt for the scenarios Si. The costs used for each scenario were obtained from Minute 309, which states the costs in 2004 MXP that the 3 irrigation districts had to invest to implement their improvements. Equation 5.8 was used to estimate $PV_{cost\ DRt_{Si}}$:

$$PV_{cost\ DRt_{Si}} = (WR_{DRt} - WD_{DRt_{Si}})\, C_{WS_{Si}} \tag{5.8}$$

where WR_{DRt} is the water right of the irrigation districts DRt, and $WD_{DRt_{Si}}$ is the new water demands of the irrigation district DRt after the implementation of the improvements analyzed in scenarios Si. The cost per unit of water saved ($C_{WS_{Si}}$) in each scenario Si was assumed to be similar to what DR005, DR090 and DR103 invested on their improvements in 2004 updated to 2016 values with annual consumer price index [128].

The economic benefits ($PV_{benefits\ DRt_{Si}}$) in Equation 5.7 include the benefits from selling the water savings from the irrigation districts DRt for HF users in the nearby shale areas. Equation 5.9 was used to estimate these economic benefits:

$$PV_{benefits\ DRt_{Si}} = \sum_{n=1}^{10} \frac{(WS_{DRt_{Si}})\,(WP_{DRt_{Si}})}{(1+i)^n} \tag{5.9}$$

where $WS_{DRt_{Si}}$ are the annual water savings from the irrigation district DRt in each scenario Si, which was estimated in each period (n) by bootstrapping from the potential annual water savings of a given year in the 60 year period simulated in the RGB WEAP model. The water price ($WP_{DRt_{Si}}$) required to offset the improvements costs in the irrigation district DRt in each scenario Si were found by setting the present value ($PV_{DRt_{Si}}$) of the costs minus benefits equal to zero. Finally, the 95% confidence interval of the water prices required to offset the shifting cost were estimated after running 1,000 iterations of the economic model to capture the uncertainty of the annual water savings that could happen in a given year.

5.3 Findings and Discussion

5.3.1 Water Availability

The widely used performance parameters criteria of reliability, resilience, and vulnerability were estimated to evaluate how the water supply would be allocated to the irrigation districts analyzed. The reliability represents the frequency at which the monthly demand is satisfied (as percentage). The resiliency shows the probability the system recovers from a deficit period (as percentage), and the vulnerability refers to the average magnitude of deficits (as Mm^3/month) [108, 109]. Equations 4.13 — 4.15 in Chapter 4 are used to determine these parameters.

The performance criteria estimated for the irrigation districts (DR050 and DR006) are shown in Table 5.3. These results are presented as the change in each performance parameter with respect with the Baseline Scenario. The performance parameters that improved are in green italic and the ones that decreased are red underlined. For instance, the reliability or frequency with which the new water demand of DR006 is satisfied increased around 45% in the 3 scenarios analyzed.

The results presented in Table 5.3 show that the irrigation districts were able to meet more frequently their new water demand in each scenario analyzed. In Scenario 1 and 3 the new water demand of DR006 was met always, and in Scenario 2 was met almost always with the exception in two months. For DR050, the water demand was met between 18—20% more times in the scenarios analyzed. In one case, the vulnerability parameter for DR050 was worse than in the Baseline Scenario. The increase of the vulnerability is because there are fewer times in which the water demands of the users are not satisfied making the average magnitude of the deficit bigger.

Table 5.3: Change of the performance criteria of the water delivered to the irrigation districts (DR050 and DR006) in Scenarios 1, 2 and 3 with respect to the Baseline scenario. In italic are the cases where the parameters improved and the parameters that decreased are underlined.

User		Scenario 1	Scenario 2	Scenario 3
Reliability Δ Baseline (%)	DR006	*45%*	*44.7%*	*45%*
	DR050	*20%*	*18%*	*18%*
Resilience Δ Baseline (%)	DR006	N/A	*98%*	N/A
	DR050	<u>-0.2%</u>	*0.2%*	*0.2%*
Vulnerability Δ Baseline (Mm^3 per month)	DR006	N/A	*-0.2*	N/A
	DR050	*-0.2*	<u>0.03</u>	*-0.1*

The annual water savings that could be allocated for HF users in Scenarios 1, 2, and 3 were analyzed by estimating a range of annual wells that could be supplied, and a range of energy that could be extracted in a 20-year period from these wells. The range of these potential annual HF wells was estimated considering (a) the upper and lower boundaries from the 95% confidence intervals estimated in each scenario, and (b) an average water withdrawal required per well of 8.77 Mgal/well [5]. The 95% confidence interval was estimated from bootstrapping from the results of the 60-year simulation of the RGB WEAP model the potential annual water savings that could be allocated for HF. This bootstrapping was conducted through 1,000 iterations to capture the uncertainty of the potential annual water savings that could happen in a given year. Figure 5.3 shows the estimated range of the annual HF wells that could be supplied with the water savings in the irrigation districts analyzed for Scenarios 1, 2, and 3. The potential HF wells that could be supplied in each irrigation district analyzed would range from 13% to 23% of the HF wells drilled in Texas' EFS in 2016

(1,320 HF wells [5]).

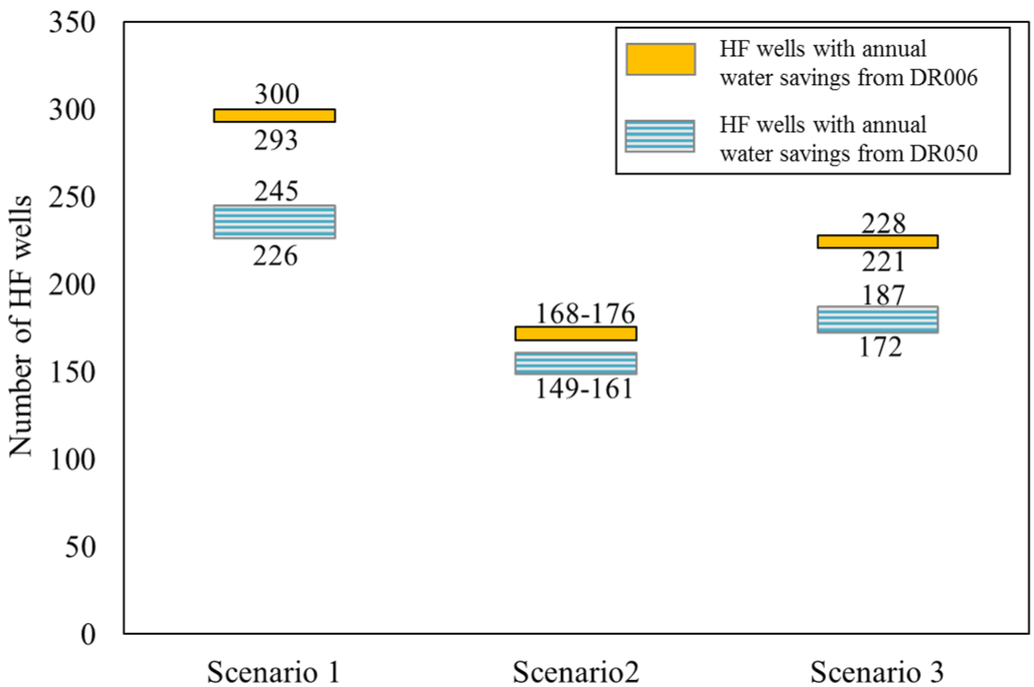

Figure 5.3: The annual HF wells that could be supplied with the water savings in each irrigation district analyzed would represent between 13—23% of the HF wells drilled in Texas' EFS in 2016.

Figure 5.4 shows an annual and cumulative range of the energy that could be extracted in a 20-year period with the HF wells that could be supplied with the water saving using the lower and upper boundaries of the 95% confidence interval in the scenarios analyzed combined. The annual and cumulative energy was estimated using the average oil and gas production in a 20-year period from 2014—2017 HF wells in Texas' EFS across the Mexican border, which was obtained from the Drilling Info database [50]. This potential cumulative energy to be extracted in 20 years with the HF wells supplied with one year of water savings ranged from 0.2 to 0.39 and from 0.27 to 0.48 Quads for DR050 and DR006, respectively. Most of this energy could be extracted during the first year, ranging from 0.09—0.14 Quads from DR050 and 0.1 to 0.17 Quads from DR006, which represents about 1—2% of Mexico's annual energy consumption assuming its current annual consumption of 7.5 Quads [73, 74].

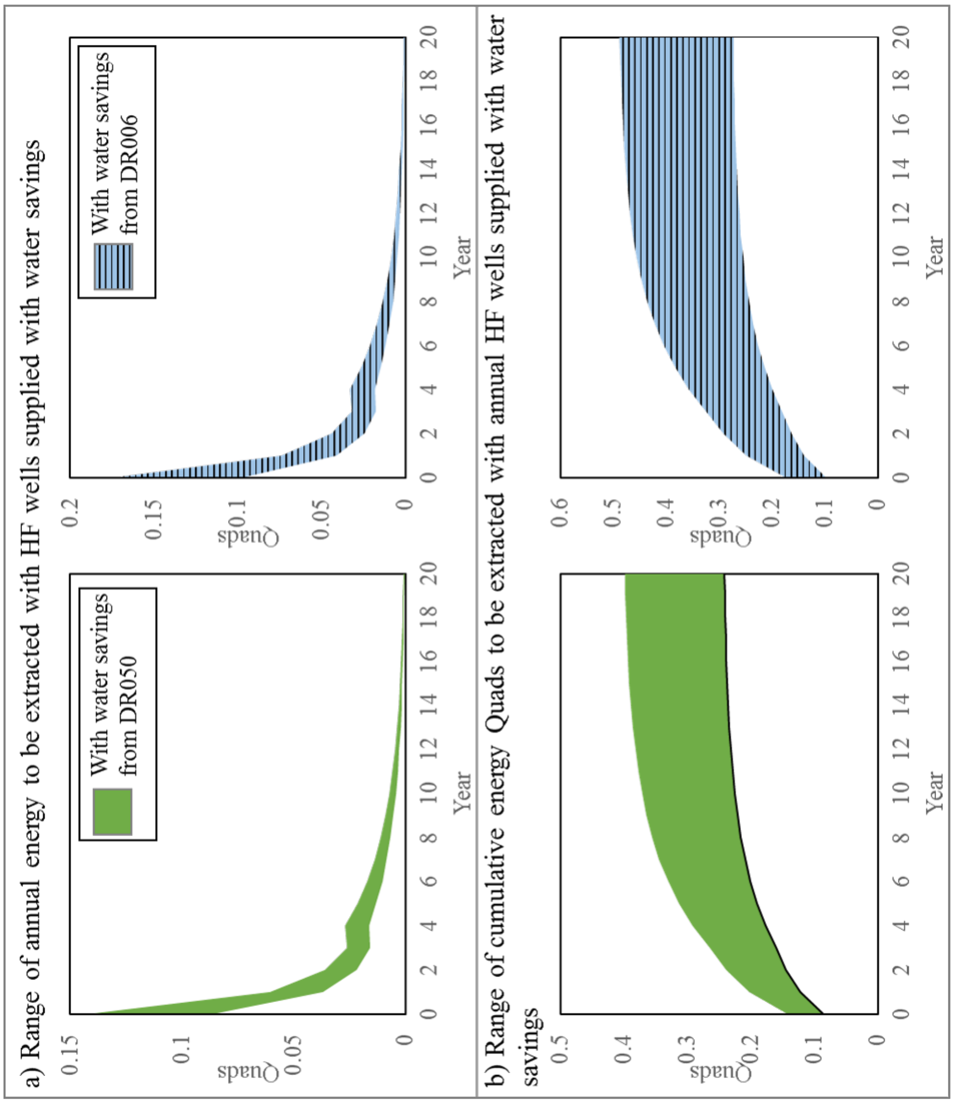

Figure 5.4: The cumulative energy that could be extracted from the annual HF wells supplied with the water savings in the scenarios analyzed would range between 0.2 to 0.39 for DR050 and from 0.27 to 0.48 Quads for DR006, from which around 35—45% could be extracted in the first year.

5.3.2 Economic Analysis

Figure 5.5 shows the breakeven prices at which the sales of the water savings from implementing the irrigation improvements in the scenarios analyzed would offset the costs of these improvements. The range shown in each scenario are the upper and lower boundaries of the 95% confidence intervals in each scenario. The 95% confidence interval was estimated from bootstrapping from the results of the 60 year simulation of the RGB water allocation model the potential annual water savings of the irrigation districts analyzed, which was allocated for HF users.

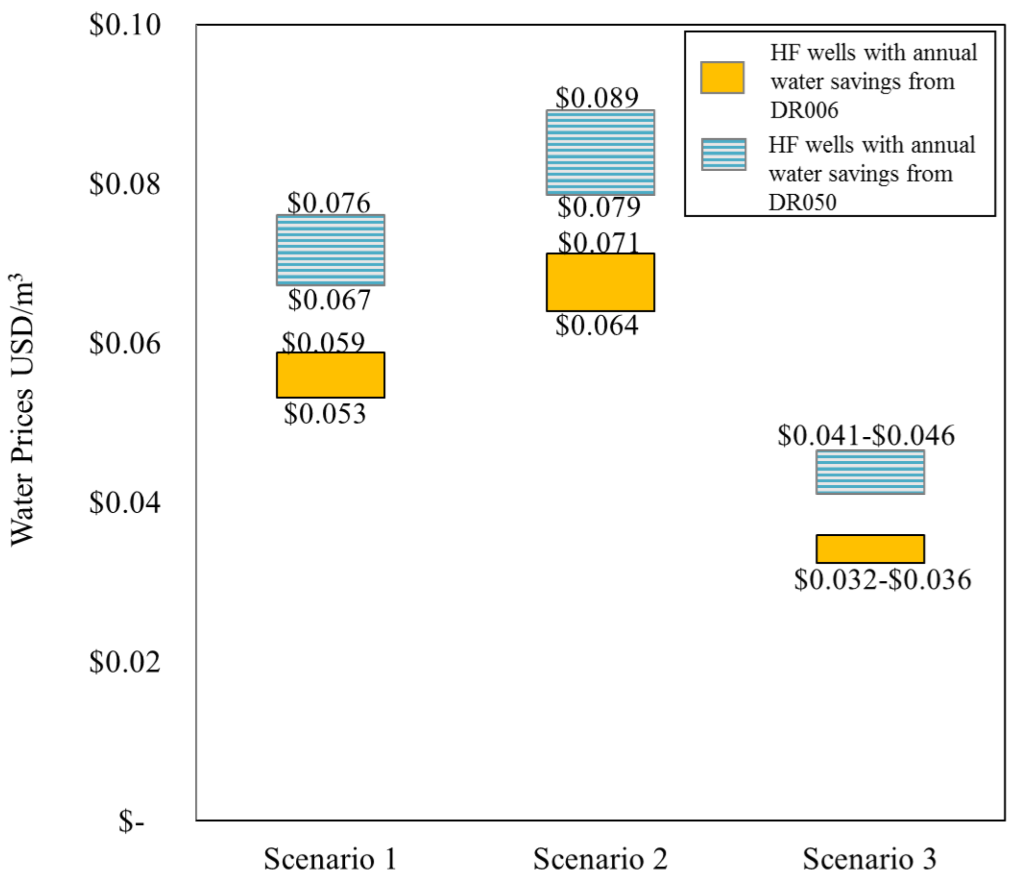

Figure 5.5: The water prices required to offset the implementation costs of the irrigation improvements seem too high for the irrigation district, but reasonable for the prospective HF users.

The water prices required to offset the cost of implementing the irrigation improvements in Scenario 3 ranged from \$0.032 to \$0.089 USD/m^3. These prices are higher than the water prices reported by some irrigation districts on the Mexican side of the RGB, which range between \$0.013 and \$0.02 USD/m^3 [126] and are similar to the price paid by irrigation districts on Texas' side of the EFS (\$0.01 USD/m^3 [1]). Furthermore, the median revenues from the crops harvested per unit of water in the irrigation districts analyzed ranged between 0.04 and 0.28 USD/m^3 from 1997—2013 [110–125]; hence, the water prices required to offset the costs implied from the implementation of irrigation improvements could be too high for irrigation districts. On the other hand, HF users in the EFS in Texas pay on average \$3.9 USD/m^3 due to the higher revenue per unit of water that this activity could generate [1]. This water price paid in the Texas' EFS is two orders of magnitude higher than the ranges of water prices estimated in the scenarios analyzed; hence, it seems that there is potential for collaboration between these two irrigation districts and prospective HF sites.

5.4 Conclusion

This case study analyzes the potential collaboration between two irrigation districts in the RGB (DR050 and DR006) and prospective HF users in three nearby shale areas which are expected to be explored and developed in the according to SENER's 5-year plan [10]. The potential collaboration would focus on (1) improving the irrigation technologies and practices to achieve water savings from irrigation, and (2) selling the water savings for HF users to offset the costs of the irrigation improvements. The following four potential scenarios were analyzed:

1. Baseline Scenario: Normal water allocation over years 1940 to 2000.

2. Scenario 1: The improvements implemented by the irrigation districts were assumed to be similar to the ones made by Irrigation District DR005 in 2004 [8]. The water savings were allocated to HF sites in the shale areas expected to be explored and developed according to SENER's 5-year plan.

3. Scenario 2: Similar to Scenario 1, but it was assumed that the irrigation technologies and practices improvements were similar to the ones made by Irrigation District DR090 in 2004 [8].

4. Scenario 3: Similar to Scenario 1, but it was assumed that the irrigation technologies and practices improvements were similar to the ones made by Irrigation District DR103 in 2004 [8].

The results suggest that implementing the irrigation improvements in Scenarios 1, 2 and 3 would increase water availability for the irrigation districts; however, this available volume is small compared to other irrigation districts and to the overall RGB basin's water demand. In Scenario 1, 2, and 3, the frequency at which the new water demand of DR050 increased between 18—20% from the baseline scenario; whereas for DR006 the demand was always satisfied in Scenario 1 and 3, and was unmet only in two months in Scenario 2. In the scenarios analyzed, the annual HF wells that could be supplied with the water savings from DR050 and DR006 would range from 149 to 245 and from 168 to 300 wells/year, respectively. These HF wells could extract between 0.2—0.39 and 0.27—0.48 Quads in a 20-year lifetime using the water savings of DR050 and DR006, respectively. Around 35%—45% of this energy could be extracted in the first year, which represents about 1—2% of Mexico's annual energy consumption assuming its current annual consumption of 7.5 Quads [73, 74].

According to the economic analysis conducted, the water prices required to offset the costs in the scenarios analyzed would range from \$0.041—\$0.089 USD/m^3 for

DR050 and \$0.032—\$0.071 USD/m^3 for DR006. These water prices are higher to what irrigation districts usually pay for water in the region (\$0.013—\$0.02 USD/m^3 [126]). On the other hand, HF users water prices are on average 3.9 USD/m^3 in the Texas' EFS, which is two orders of magnitude higher than the ranges of water prices estimated in the scenarios analyzed. Therefore, it seems that there is potential room for collaboration between these two irrigation districts and potential HF sites. Future work could consider the impacts of changes in weather patterns derived from climate change to the scenarios analyzed, which could decrease the water savings to be allocated for new users and increase the water prices required to offset the shifting costs.

Chapter 6

Conclusion

Mexico's government enacted an energy reform in 2013 that aims to foster competitiveness and private investment throughout the energy sector value chain. As part of this reform, it is expected that extraction of oil and gas via HF will increase in Mexico's five shale basins (e.g. Burgos, Sabinas, Tampico, Tuxpan, and Veracruz). The potential development of shale resources could face different environmental and social challenges. One of the environmental challenges, that could become a social challenge as well, relates to the water quantity it requires. The impacts from HF would vary depending on the water availability and competing demands at a local level [1, 53, 129]. This dissertation presents a framework to assess the potential water available for the development of shale resources through HF in Mexico by centering on (1) estimating the water available in aquifers and watersheds overlaying the shale resources, and (2) analyzing different strategies to increase water availability for HF in water stressed areas. Following this framework, this dissertation addressed the following research objectives:

1. Determining current water availability in the aquifers and watersheds overlaying the prospective shale resources in Mexico.
2. Estimating the potential produced water from HF that could be reused to develop shale resources in prospective areas in the Burgos Basin across the border with Texas.

3. Evaluating the potential increase in water availability for either current users (e.g. irrigation districts) or potential HF users in the middle and lower Rio Grande/Bravo basin (RGB) due to a shift of:

    - current energy production facilities to more efficient energy sources (from coal to gas) and power plant technology (from steam cycle to combined cycle), including an estimation of the breakeven prices at which the surplus water sales plus the economic benefits from shifting the technology and energy sources would offset the costs implied on this shift.
    - current irrigation practices and technologies to more water efficient technologies and practices, including an estimation of the breakeven price at which the surplus water sales would offset the investment cost of the irrigation improvements.

The analysis conducted throughout these research objectives could assist policymakers as a starting point in the development of strategies for managing the water resources available to develop shale resources in Mexico. Higher resolution data could be used to estimate the likelihood of the water available for HF with less uncertainty in specific areas, as well as the spatial and temporal variations. The following sections summarize the conclusions from the three research objectives.

6.1 Summary

6.1.1 Assessing water availability for shale development in Mexico

Chapter 2 presented an analysis that intends to serve as a starting point for the development of strategies for managing new HF demands in the context of constrained water resources. The analysis consisted on conducting a multilayer geospatial methodology to determine the spatial location and potential volume of water available in the aquifers and watersheds that overlay the five shale basins in Mexico (e.g. Burgos, Sabinas, Tampico, Tuxpan, and Veracruz).

The most conservative scenario analyzed could assist to determine and identify the potential areas with water availability for HF that would not increase water stress in the watersheds and aquifers that are overlaying the shale areas. Under this scenario, the average annual water available could be used to supply HF wells that can extract on average 18.05 Quads over a 20-30 year lifetime period, which represents around 7% of the energy that Mexico could consume in 30 years. However, the geographic distribution of the water availability could represent a challenge for extracting the shale recoverable resources in some areas. Most of this water is located closer to the Gulf of Mexico; whereas the areas with less water availability are in Northern Mexico, where the larger reserves are located.

6.1.2 Assessing potential reuse of produced water from hydraulic fracturing activity in prospective areas of the Burgos Basin (Mexico) across the Texas border

Chapter 3 presented a method to evaluates the potential produced water from HF activities that could be reused to develop shale resources by focusing on three unconventional areas expected to be developed in the Burgos Basin, which is the shale basin with around 70% of the recoverable shale resources in Mexico. These areas overlay the RGB basin, which has over-allocated water rights [58–60], and is considered to be under severe water stress [61]. The analysis consisted on a temporal analysis that includes (1) an estimation of PW production decline curves of potential HF wells in the region using empirical observations and empirical decline models with data from the Texas' Eagle Ford Shale, and (2) a drilling schedule forecast of the HF wells that could be drilled in the 3 unconventional areas analyzed.

Results suggest that the potential PW from HF activity in these areas could be reused to extract between 60 to 158 Trillion BTUs of energy in the form of oil and gas throughout a 20-year period. This cumulative energy represents from 0.37 to 1% and 0.01 to 0.03% of recoverable shale resources in the corresponding overlaying areas in the Burgos Basin (oil and dry gas area, respectively). The peak of production would happen in year 5 with between 8.5 and 22.2 Trillion BTUs, which would represent between 0.1% and 0.3% of Mexico's annual energy consumption assuming its current annual consumption of 7,500 Trillion BTUs/year. More research needs to be conducted to determine (1) the quality of the PW in these areas, (2) the treatment required to reuse the PW in other HF wells, and (3) the costs associated with the treatment and management of the produce water and the brine waste from the treatment process.

6.1.3 Evaluating increase in water availability for current and potential new users due to a shift in power plant and irrigation technologies in the Rio Grande/Bravo

6.1.3.1 Shift in power plant technology

Chapter 4 presented a methodology to assess the potential changes in water availability in RGB basin due to a shift of current energy production facilities to more water efficient energy sources (from coal to gas) and power plant technology (from steam cycle to combined cycle). This technology shift would generate water savings and thus, increase water available to either current users (irrigation districts) or new potential HF users. The analysis consisted in (a) coupling a water allocation model of the RGB with a power plant water demand calculator that depends on energy fuel source and power plant technology, (b) simulating different scenarios in which the water savings would be allocate to other potential users (e.g. irrigation districts and HF users), and (c) estimating the breakeven prices at which the sales of water savings plus the economic benefits from shifting the technology and energy sources would offset the costs implied on this shift.

According to the scenarios analyzed, switching the coal-fired power plants to natural gas combined cycle would increase water availability for current (e.g. irrigation districts) and potential HF users; however, this available volume is small compared to the overall RGB basin's water demand. Under the scenario in which the water savings were allocated for HF users, around 0.78 to 1.02 Quads could be extracted in a 20-year lifetime of the HF wells supplied with this water, which would represent between 11—18% of resources in the oil area in the Burgos basin. The water prices required for HF users to offset the power plant technology shift ($1.3-$6.3 USD/m^3) would be similar to the water price paid in Texas' EFS between 2009 and 2014 (on average $3.9 USD/$m^3$ [1]). The water prices estimated for irrigation districts to offset this shifting costs ($1.84—$12.88 USD/m^3) seem to high for the irrigation districts analyzed, which generated a median revenue of between $0.08 and $0.28 USD/$m^3$ from the crops harvested per unit of water from 1997-2013 [110–125].

6.1.3.2 Shift in irrigation technology

Chapter 5 presented a methodology to assess the potential changes in water availability in the RGB basin due to a shift of two irrigation districts to more water efficient practices. This shift would generate water savings and thus, increase water available to include new potential users in the region, such as HF users. The analysis consisted in (a) coupling a water allocation model of the RGB with a irrigation water demand calculator that takes into account changes on water demand due to a shift in irrigation technologies and practices, (b) simulating different scenarios in which water savings vary depending on the potential irrigation improvements, and (c) estimating the breakeven prices at which the sales of the water savings would offset the costs from shifting the irrigation technology and practices.

According to the scenarios analyzed, implementing the irrigation improvements would increase the frequency at which the water demand of the irrigation districts is met and could generate annual water savings that could be allocated for HF users. The annual water savings from each of the two irrigation districts analyzed could be used to extract between 0.25 and 0.5 Quads in a 20-year lifetime, which would represent between 4—8% and 0.1—0.15% of resources in the oil and dry gas areas in the Burgos Basin that each irrigation district overlay. The water prices required to offset the irrigation improvement costs (0.03—0.09 USD/m^3) would be higher than the water prices reported by other irrigation districts in upstream areas in the RGB ($0.013—$0.02 USD/m^3). Furthermore, the median revenues from the crops harvested per unit of water in the irrigation districts analyzed ranged between $0.04 and $0.28 USD/$m^3$ from 1997-2013 [110–125], while HF users in the EFS in Texas pay on average $3.9 USD/$m^3$ due to the higher revenue per unit of water that this activity could generate [1]. Therefore, HF site could be the user most likely to pay for the water savings derived from shifting the irrigation technologies and practices in the irrigation districts analyzed.

6.2 Future Work

Future work could consider other strategies that includes accounting for (a) other water sources that are not in the system, (b) collaboration with other water users in the region, and (c) alternatives of non-aqueous fracturing fluids. The water sources that are not considered in the system could include degraded water quality sources (e.g. brackish groundwater, and seawater), and water transferred from different watersheds or aquifers with high water availability. It is relevant to conduct more research to understand the volumes and distribution of brackish aquifers in the regions overlaying the shale resources, and the economic and environmental impacts on using (and potentially treating) these degraded water sources. Also, it is important to conduct a holistic analysis of the potential impacts derived from transferring water from different watersheds. On the other hand, the potential collaboration between users in the region could include irrigation districts, HF users, and industrial users (e.g. cement factories, pulp and paper companies, and power plants) in the region, and water prices could be determined by conducting a water market analysis to assess the value that each type of user could derive from the water used as input in their activities. This analysis should also consider the potential environmental and social impacts. Also, future research should examine the seasonality variation of the potential water availability, the temporal demand from prospective HF users, and the infrastructure required to mitigate this potential disparity. In addition, future research could be conducted to examine the water availability variation under extreme weather conditions derived from climate change. This variation would impact the current and potential water users with more sever, longer, and more often drought and/or wet periods. A decision analysis of the strategies that includes several scenarios with different probabilities of future extreme weather conditions could be developed. This analysis could assist decision makers and the different players in the region of the most optimal strategies and collaboration opportunities under these potential future weather patterns.

Appendix

List of Acronyms

- Bbbl: Billion barrels of oil
- Bgal: billion gallons
- BTU: British termal unit of energy
- CCP: Coal fired power plant
- CFE: Mexico's Federal Electricity Commission
- Co: Coal
- Conagua: Mexico's Water Comission
- CRWR: Center for Research in Water Resources
- EFS: Eagle Ford Shale
- EIA: U.S. Energy Information Administration
- EPA: United States Environmental Protection Agency
- EUR: Estimated Ultimate Recovery
- gal/Quads: gallons per Quadrillion British termal unit of energy
- gal: gallons
- GWAI: Groundwater Availablity Index
- HF: Hydraulic Fracturing
- IMTA: Mexican Institute of Water Technology
- IWBC: International Water Boundary Commission
- Mgal/well: Million gallons per well
- Mm3: Million cubic meters
- MXP: Mexican pesos
- NG: Natural Gas
- NGCC: Natural gas combined cycle

- Pemex: Mexico's Oil Company
- PW: Produced Water
- Q1: Quartile 1 (25th percentile)
- Q3: Quartile 3 (75th percentile)
- Quads: Quadrillion british thermal units
- RGB: Rio Grande/Bravo
- RR: Risked Recoverable Resources
- SENER: Mexico's Department of Energy
- SWAI: Surface Water Availability Index
- TCEQ: Texas Commission on Environmental Quality
- Tcf: Trillion cubic feet
- U.S.: United States
- USD: United States dollars
- WA: Water Availability
- WEAP: Water and Evaluation and Planning

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Vita

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